Antinuclei Production with ALICE at the LHC

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Workshop @Snellius

Light Anti-Nuclei as a Probe for New Physics

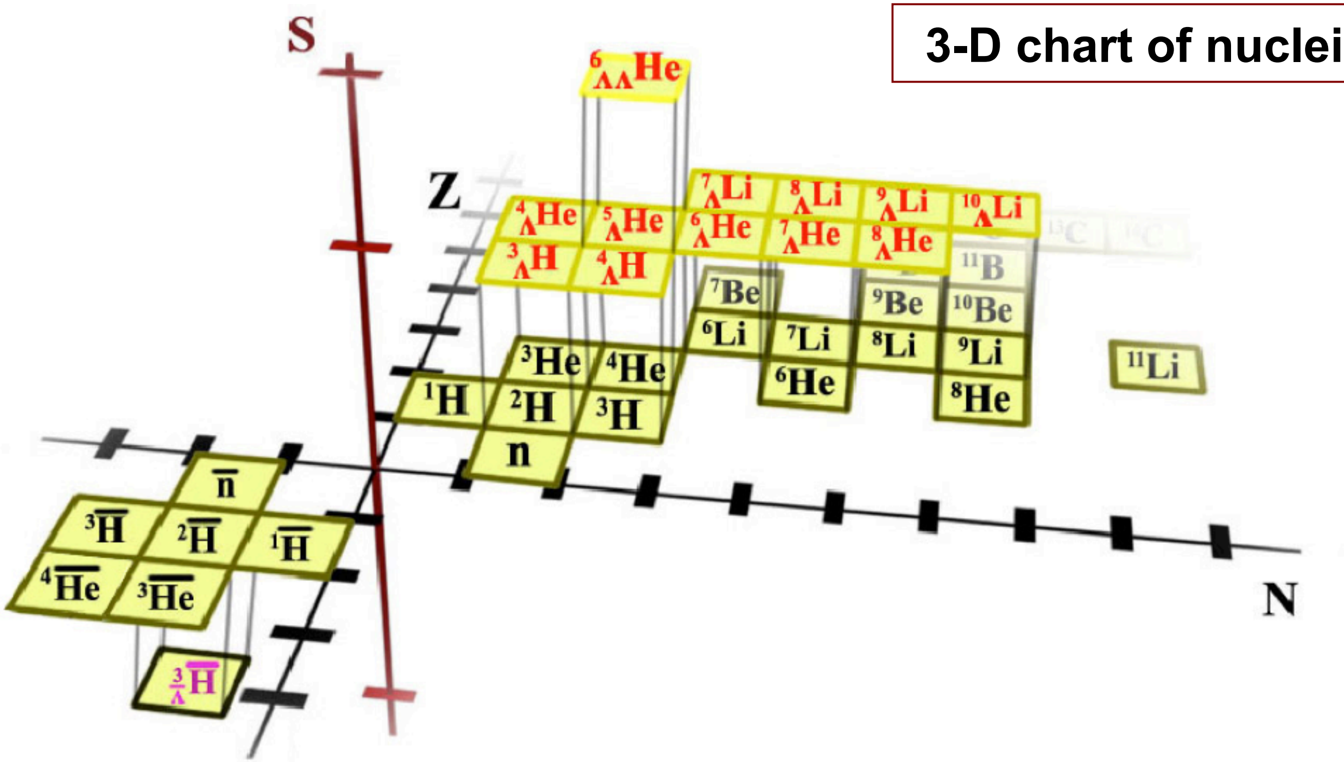
14 - 18 October 2019, Leiden, the Netherlands

Outline

- Introduction & Motivation
- LHC facility and ALICE experiment
- (Anti-)nuclei identification
- Recent results from pp, p-Pb and Pb-Pb collisions as a function of multiplicity
- Anti-deuteron inelastic cross-section measurement
- Summary
- Outlook: ALICE Upgrade

Introduction & Motivation

Introduction: Light (anti-)nuclei chart

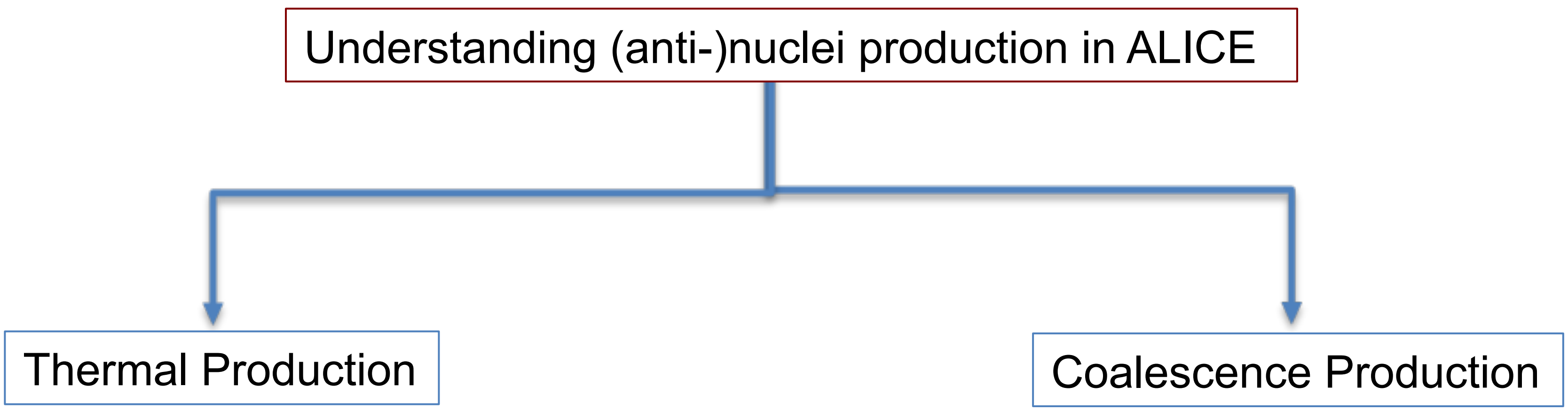


Anti-hypertriton is the lightest anti-hypernucleus, first observed by STAR experiment in 2010 [Science 328 (2010) 58].

Anti-alpha is the heaviest anti-nucleus observed so far. First observed by STAR experiment in 2011 [Nature 473 (2011) 353].

Introduction: (Anti-)nuclei @ LHC

- ➢ LHC high energy collisions:
  - Equal number of quarks and anti-quarks: u, d and s
  - Produce significant abundance of light matter and anti-matter
- ➢ Ideal facility to study nuclei and anti-nuclei production
- ➢ Provides collisions at various systems and energies
  - Systematic study of (anti-)nuclei production



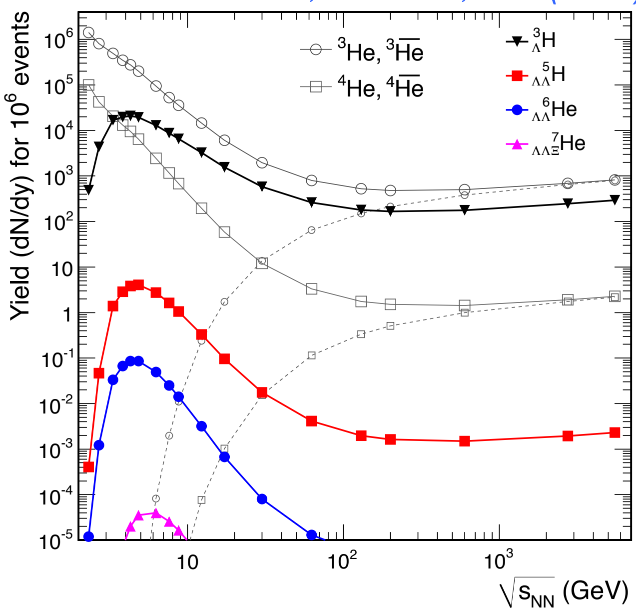
Introduction: Thermal production

- At chemical freeze-out: Particle yields get fixed
- At LHC energies ($\mu_B \approx 0$) the abundance is determined by thermodynamic equilibrium

$$\frac{dN}{dy} \propto \exp\left(\frac{-m}{T_{chem}}\right)$$

- Nuclei (having large mass) are more sensitive to T_{chem}

A. Andronic et al., PLB 697, 203 (2011)

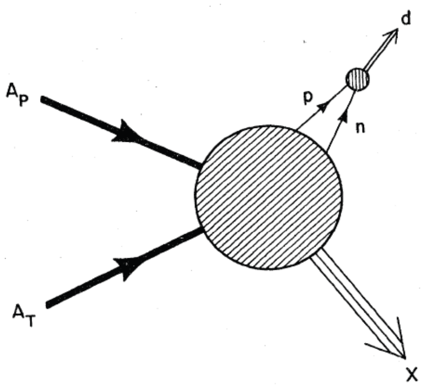


Introduction: Coalescence Production

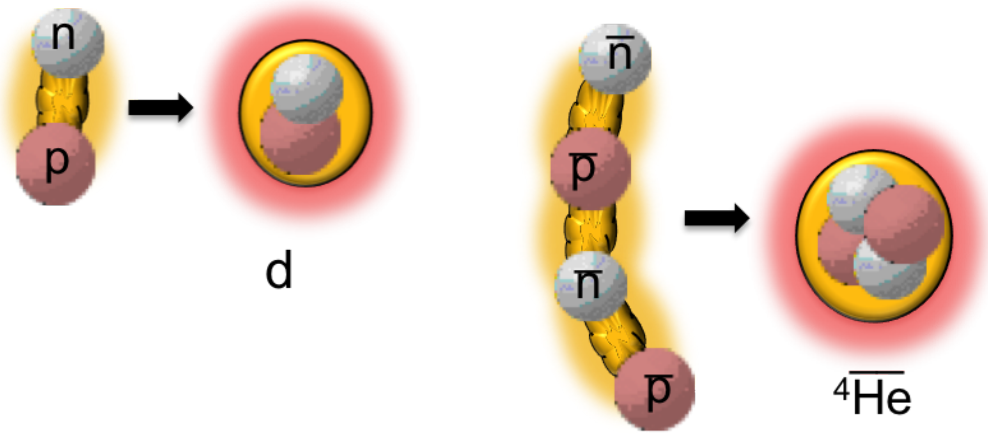
Coalescence model: (Anti-) (hyper) nuclei formation requires (anti-) nucleons and/or (anti-) hyperons to be close in phase space.

Produced (anti-)nuclei

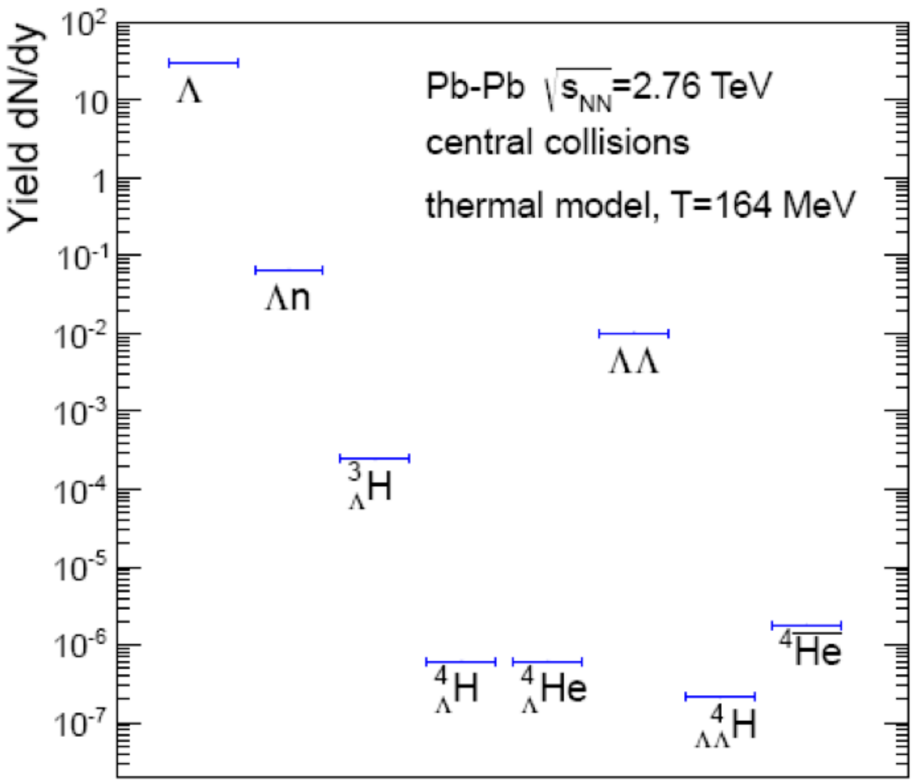
- can break apart (small binding energy) and
- can be regenerated by final-state coalescence



J. I. Kapusta, PRC 21, 1301 (1980)



Introduction: Exotic searches

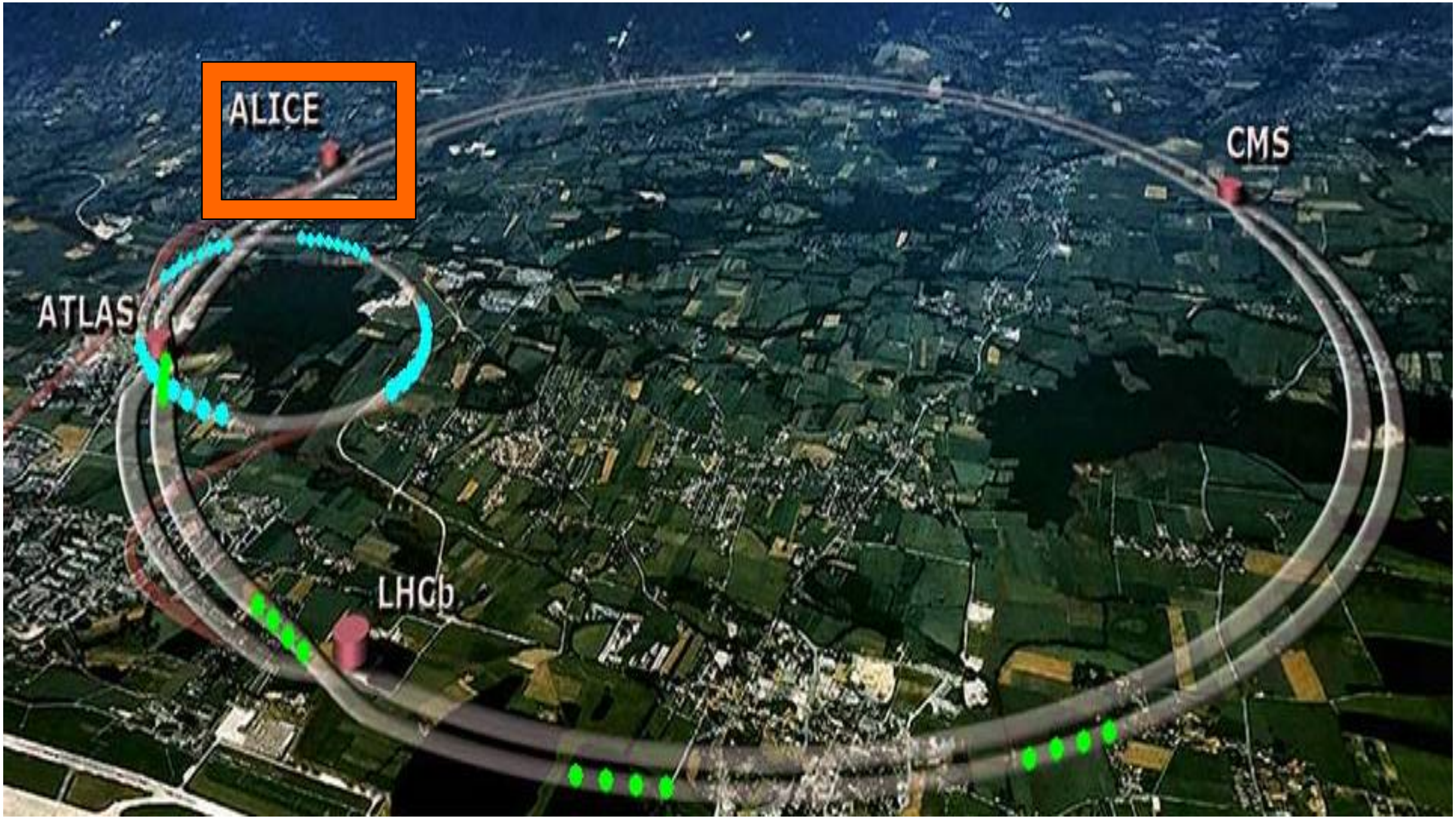


A. Andronic et al., PLB 697, 203 (2011) and references therein

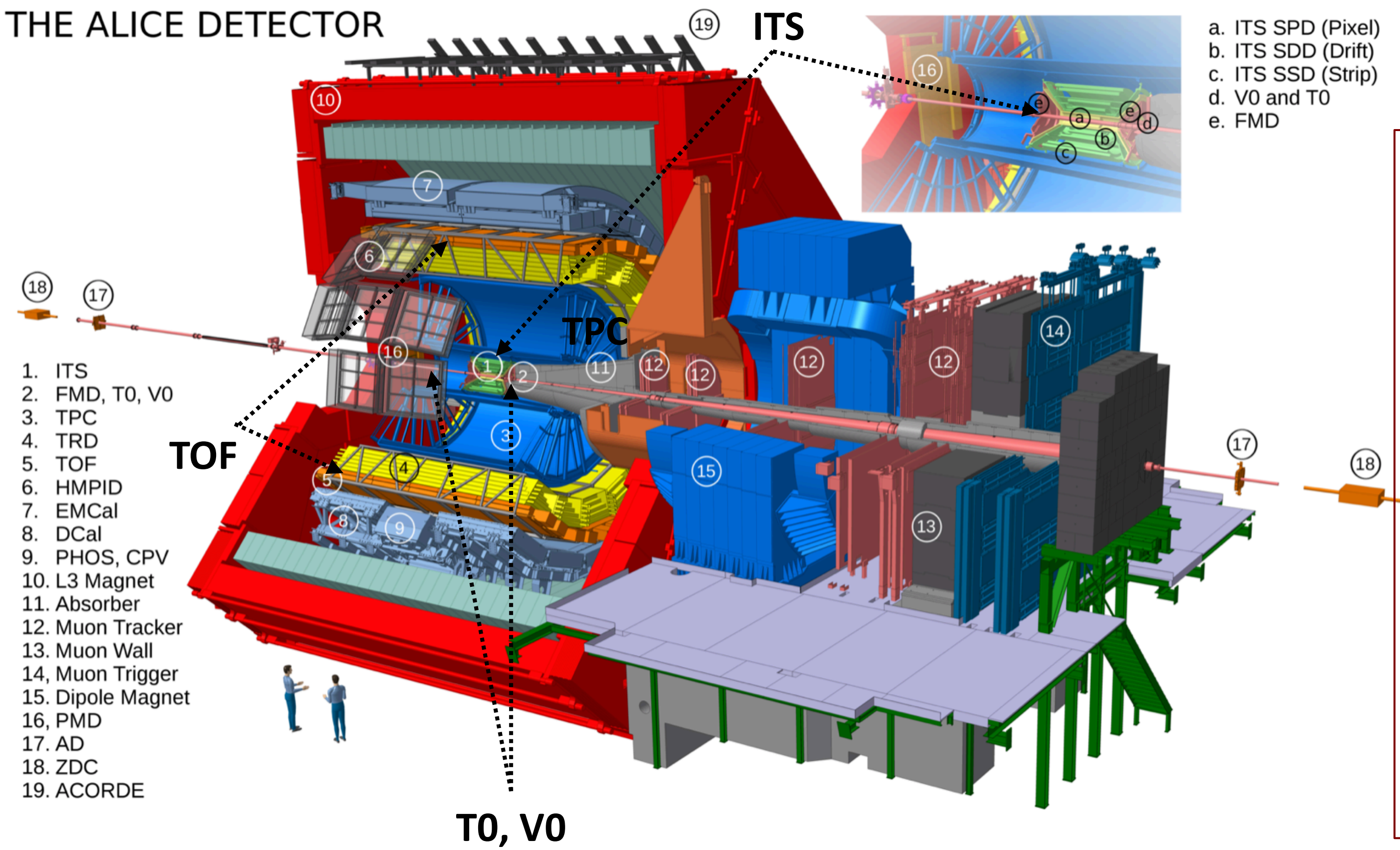
- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states.
- Search for rarely produced anti- and hyper-matter.
- Test model predictions, e.g. thermal and coalescence

LHC & ALICE Experiment

Large Hadron Collider (LHC)



A Large Ion Collider Experiment (ALICE)



Main Detectors:

ITS (|η|<0.9)

-- 6 layers silicon detectors
-- Trigger, vertex, tracking, PID (d*E*/d*x*)

TPC (|η|<0.9)

-- Gas-filled cylindrical barrel, MWPC readout
-- Tracking, PID (d*E*/d*x*)

TOF (|η|<0.9)

-- Multigap RPC
-- PID (time-of-flight)

T0 (4.6<η<4.9 and -3.3<η<-3.0)

-- 2 arrays of Cherenkov's (T0A, T0C)
-- Luminosity, **vertex**, event collision time

V0 (2.8<η<5.1 and -3.7<η<-1.7)

-- Forward arrays of scintillators (V0A and V0C)
-- Trigger, beam gas rejection, **multiplicity, centrality**

ALICE Data Collection: 2009-2018

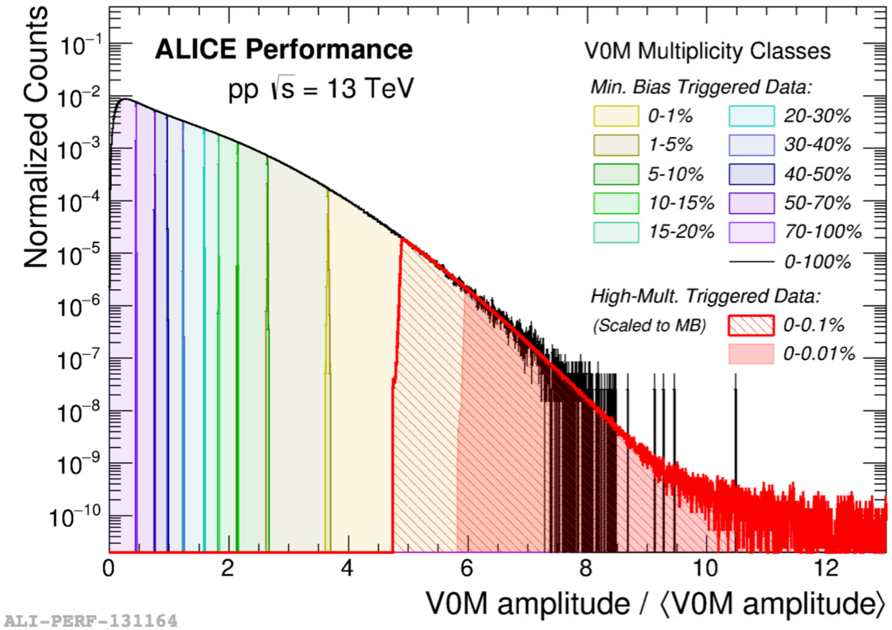
ALICE

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	2018	5.02	~0.9 nb^{-1}

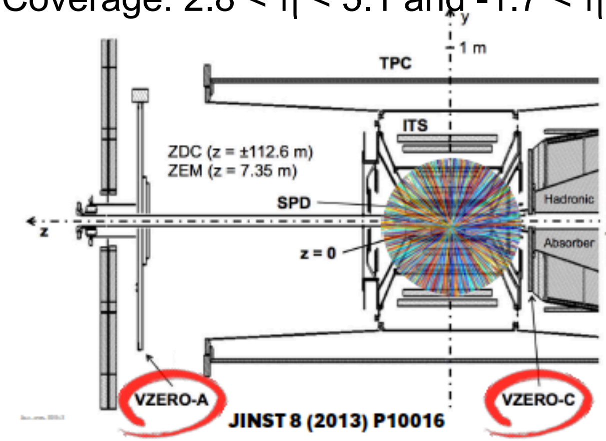
Vast data set in different systems (pp, p-Pb, Xe-Xe, and Pb-Pb) and energies

Multiplicity/centrality selection

Multiplicity is defined as the average number of charged particles per unit rapidity per event (<dN_{ch}/dη>).

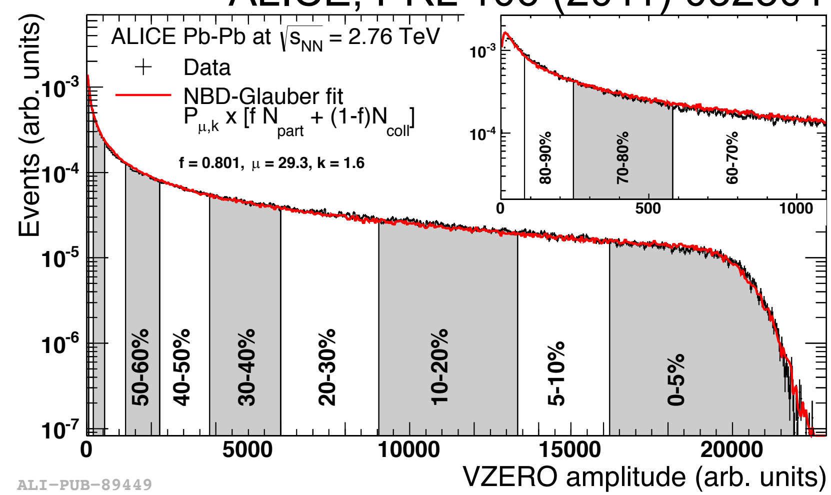


V0 Coverage: 2.8 < η < 5.1 and -1.7 < η < -3.7

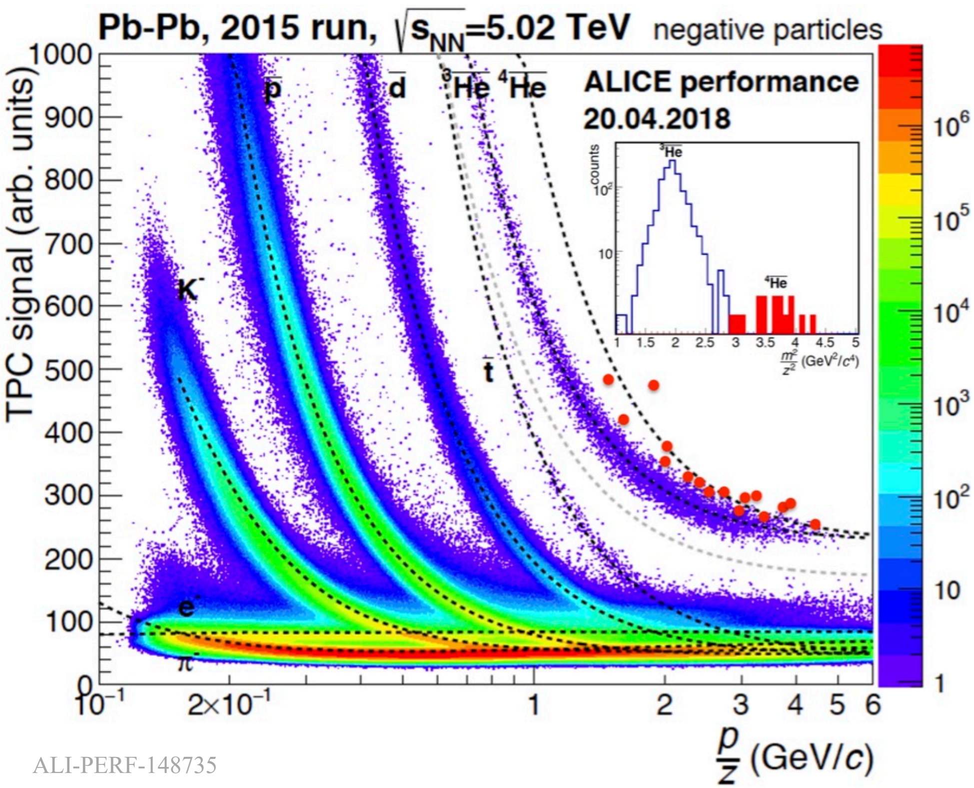


- Slicing in event activity classes is based on the charge deposited in the V0 detector at forward rapidity.
- For each class, the event multiplicity is measured at mid-rapidity (|η|< 0.5) in the SPD, in order to avoid selection biases.

ALICE, PRL 106 (2011) 032301



Nuclei identification: Time Projection Chamber

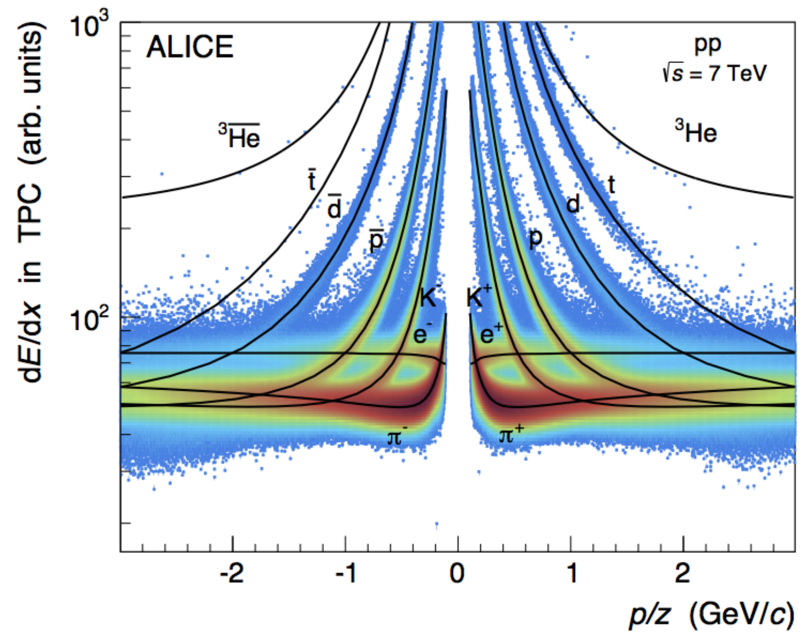


ALI-PERF-148735

Light nuclei and anti-nuclei are identified using dE/dx measurement in the TPC.

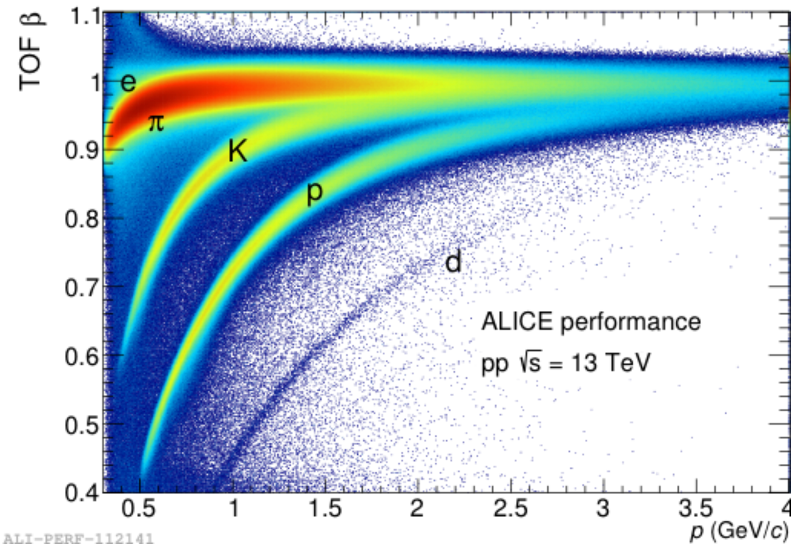
Deuterons $0.5 \leq p_T \leq 1.4$ GeV/c, and ^{3}He between $1.5 < p_T < 7$ GeV/c.

$^{4}\overline{He}$ is the heaviest anti-particle observed so far: 16 candidates in Pb-Pb at 5.02 TeV



ALI-PUB-108109

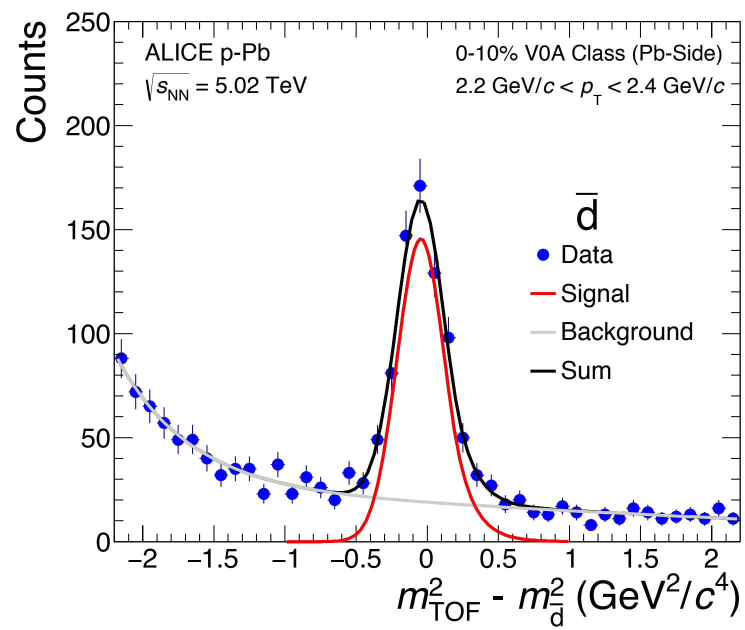
Nuclei identification: Time-Of-Flight



- Coverage: $|\eta| < 0.9$
- Multi-gap resistive plate chamber
- Particle Identification via velocity determination

Deuterons above 1.4 GeV/*c* are identified using velocity measurement with the TOF detector and extracting the yield from the Δm^2 distribution.

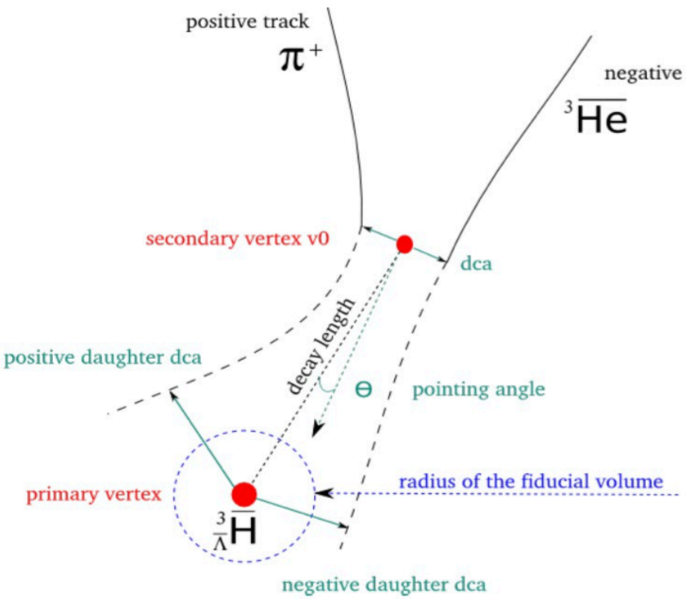
$$m^2_{TOF} = \frac{p^2}{c^2}\left(\frac{c^2 t^2_{TOF}}{l^2_{track}} - 1\right)$$



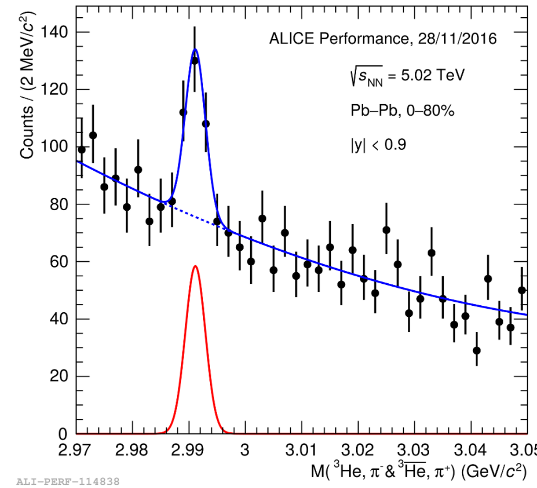
Hypertriton identification

$^{3}_{\Lambda}H$ ($^{3}_{\Lambda}\overline{H}$) – Lightest strange nucleus

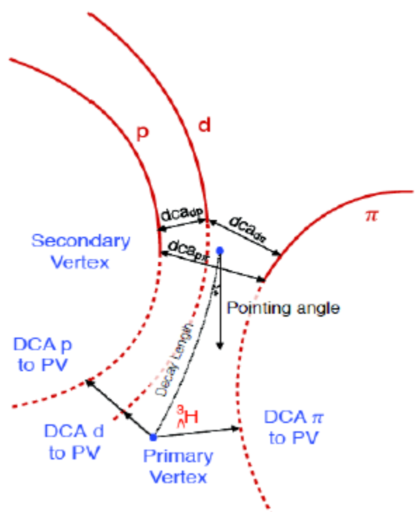
Hypertriton (M = 2.991 GeV/c^2) signal extracted using invariant mass of decay products.

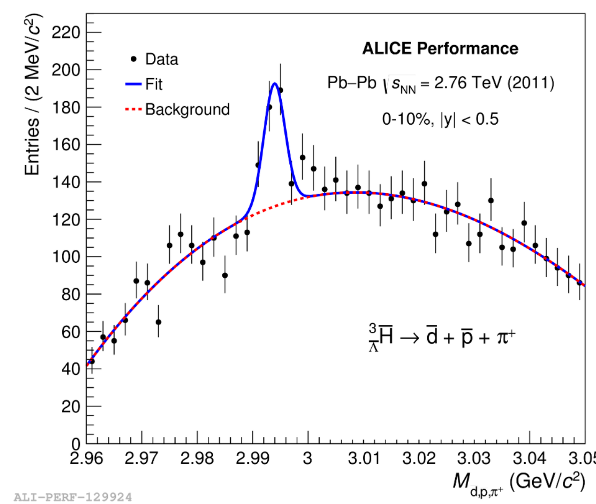


$$^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$$



$$^{3}_{\Lambda}\overline{H} \rightarrow \overline{d} + \overline{p} + \pi^{+}$$

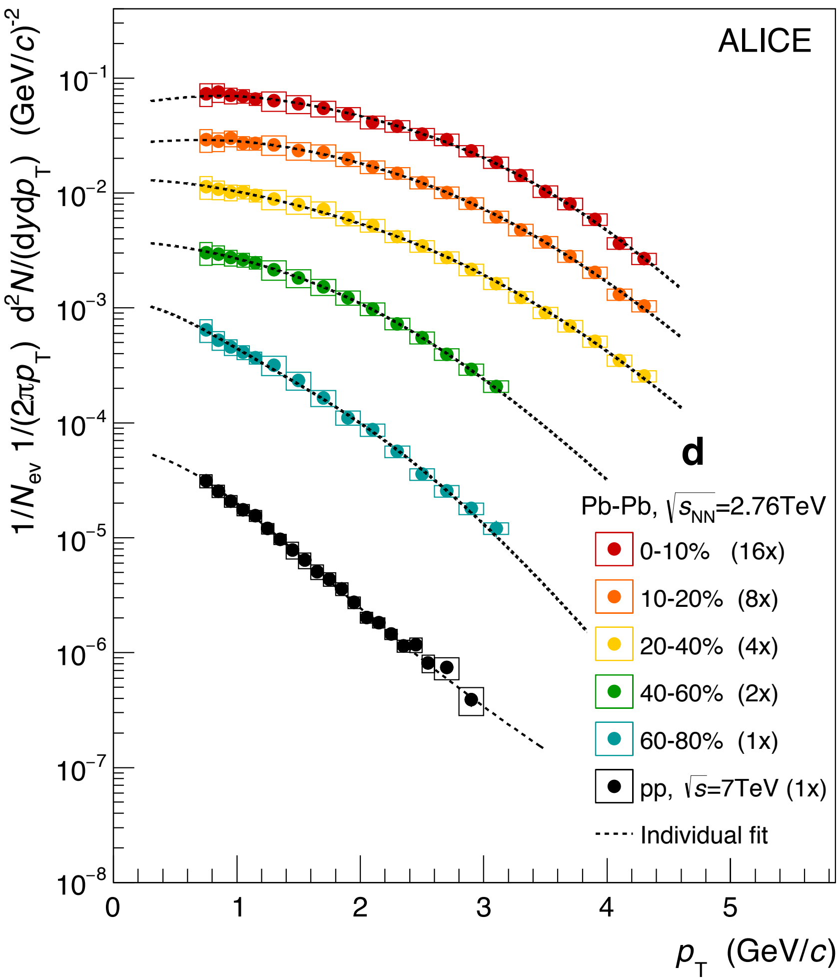


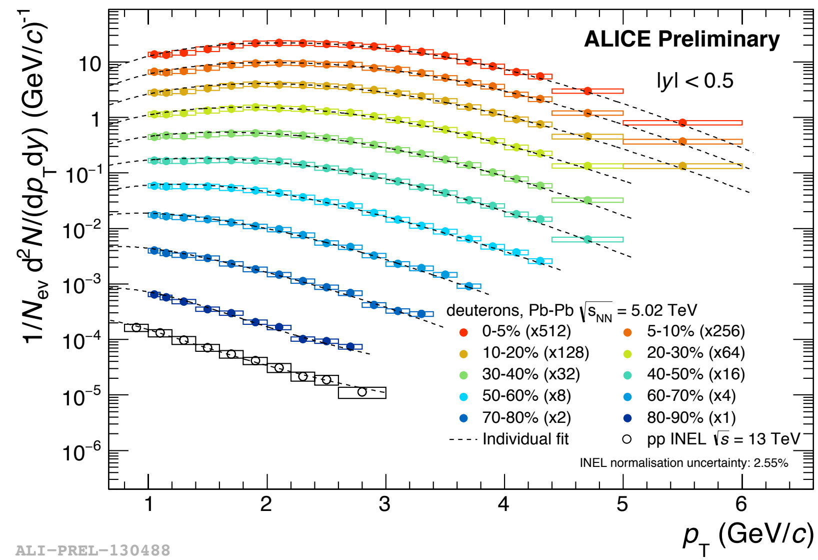


Invariant Yield and Ratios

Deuteron production at LHC (in Pb-Pb collisions)

ALICE, PRC 93 (2015) 024917



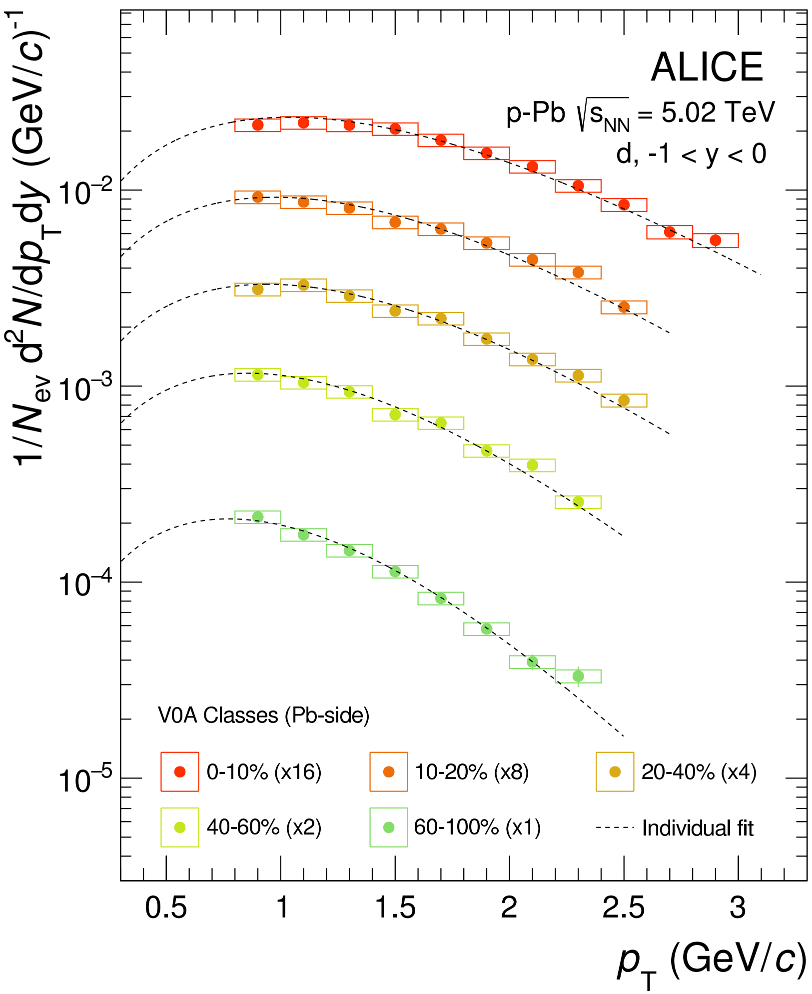


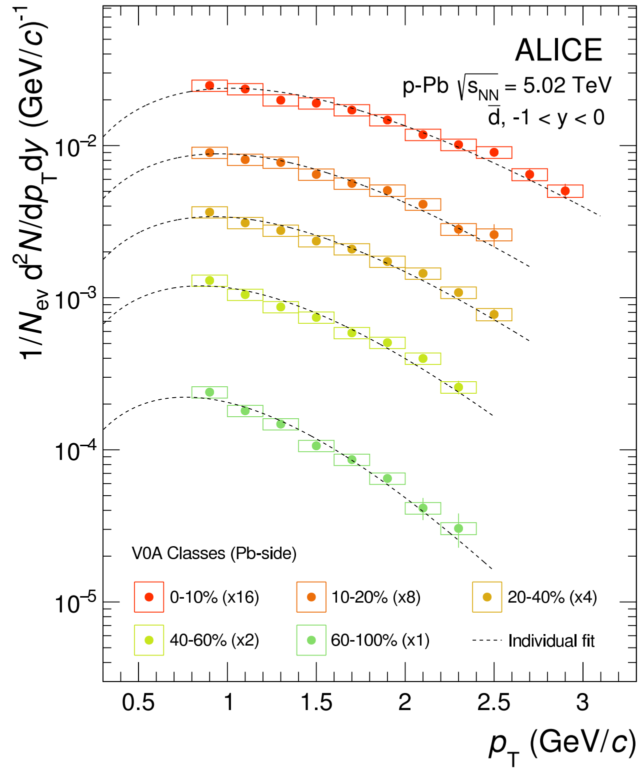
- ✓ The Blast-Wave function (*) fits the data well in Pb-Pb.
- ✓ Fit used for extrapolation of yield to unmeasured low and high p_T region.
- ✓ Spectra become harder with increasing multiplicity/centrality → consistent with radial flow.

(*) *E. Schnedermann et al., PRC 48, 2462 (1993).*

Deuteron production at LHC (in p-Pb collisions)

ALICE Coll.: arXiv:1906.03136 [nucl-ex]

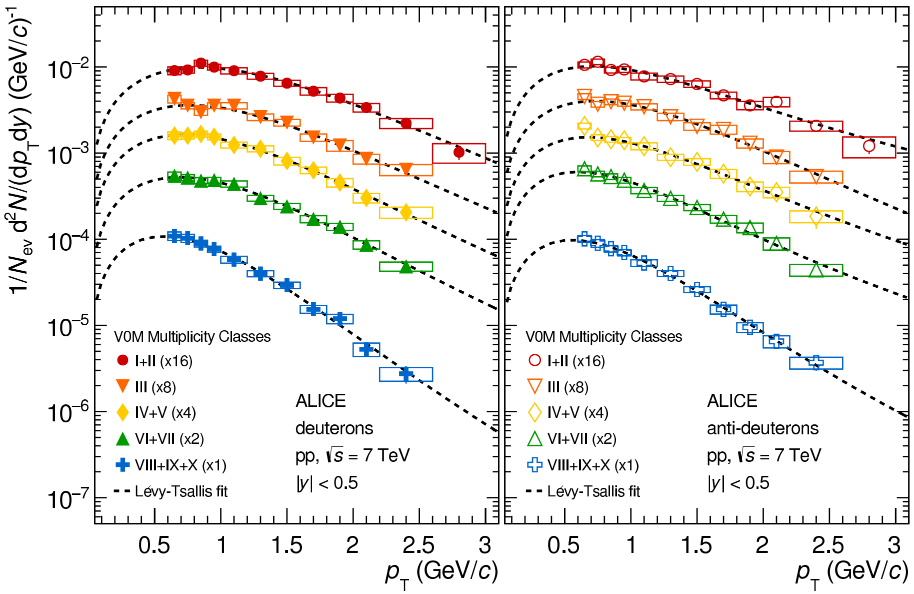


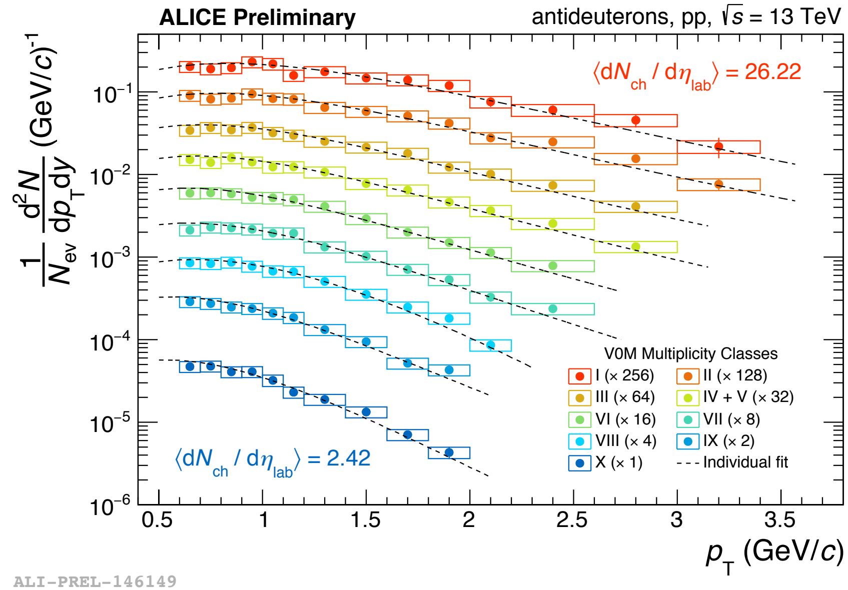


- ✓ The transverse momentum distributions are fitted with m_T-exponential function.
- ✓ Fit used for extrapolation of yield to unmeasured low and high p_T region.
- ✓ Spectra become harder with increasing multiplicity as observed in Pb-Pb.

Deuteron production at LHC (in pp collisions)

ALICE, PLB 794 (2019) 50-63



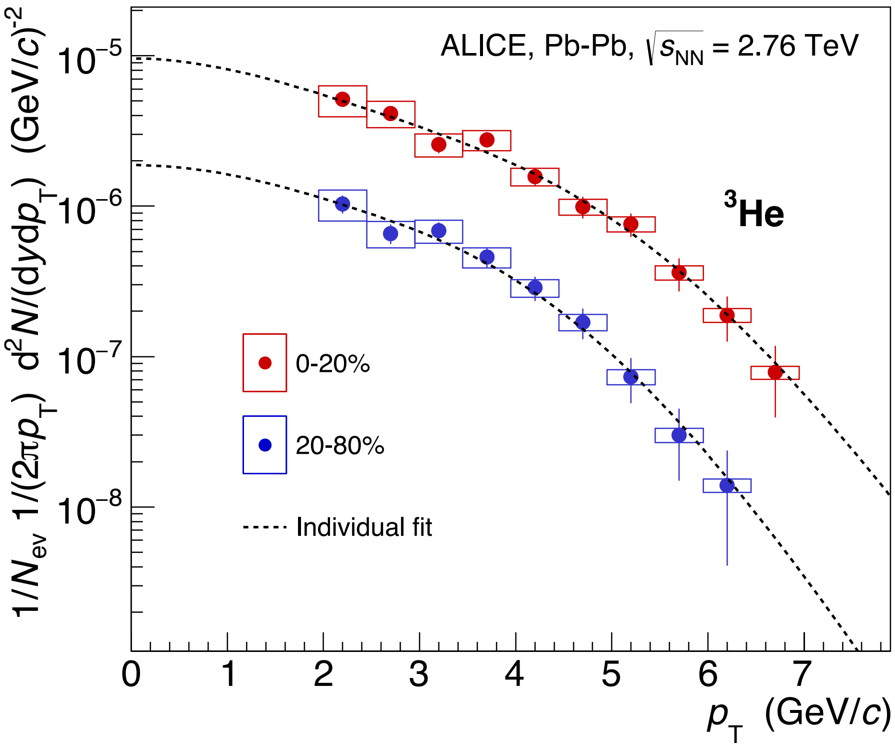


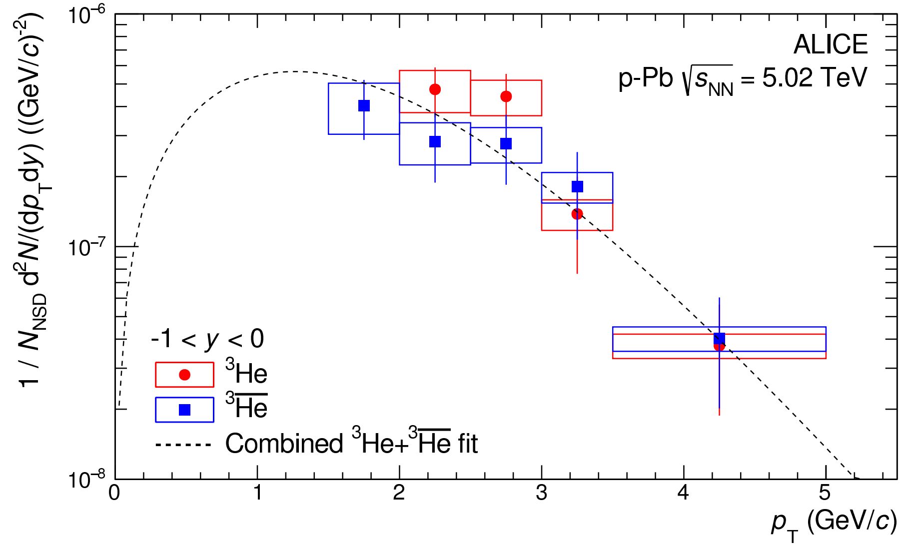
- ✓ The Levy-Tsallis function (*) fits the data well for all multiplicity classes in pp collisions.
- ✓ Fit used for extrapolation of yield to unmeasured low and high p_T region.
- ✓ Hardening of spectra with increasing multiplicity is observed, less pronounced than in p-Pb and Pb-Pb.

(*) C. Tsallis, J. Stat. Phys. 52, 479 (1988).

^{3}He production in Pb-Pb and p-Pb

ALICE, PRC 93 (2015) 024917

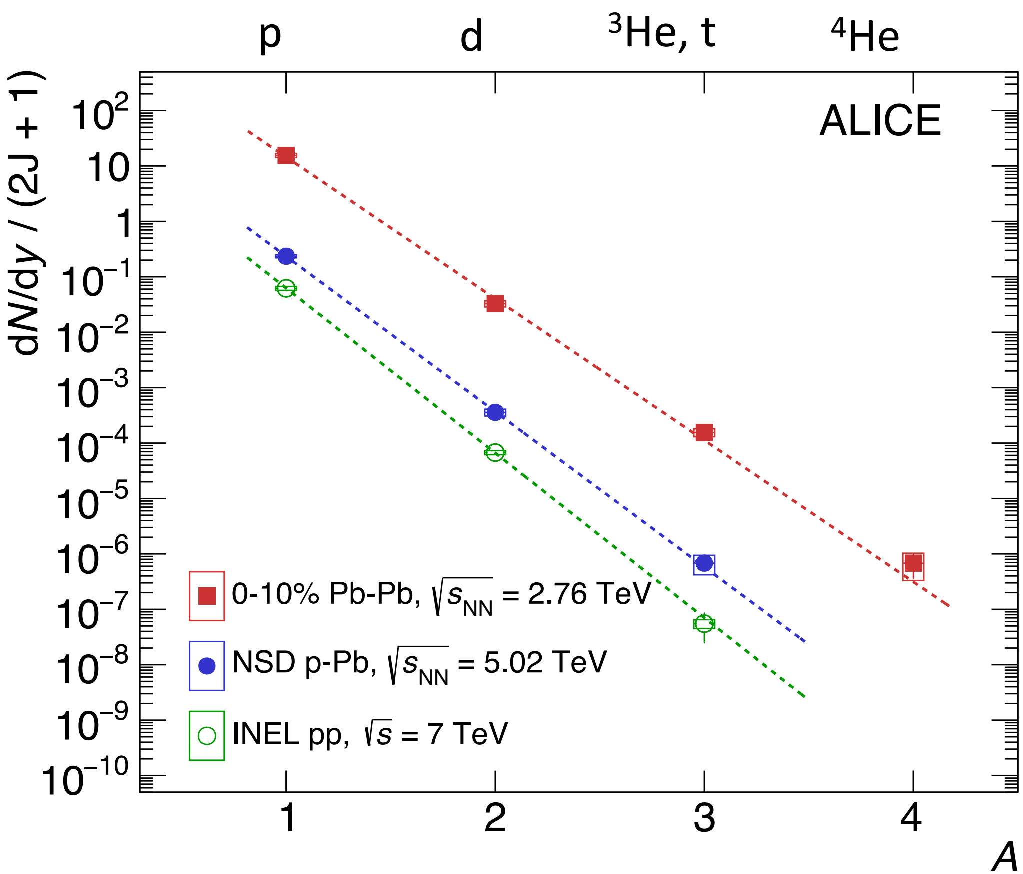




ALICE Coll.: arXiv:1906.03136 [nucl-ex]

Dashed curve represents individual Blast-Wave fits in Pb-Pb and m_T exponential in p-Pb collisions.

Mass dependence of yield



ALICE Coll.: arXiv:1906.03136 [nucl-ex]

Thermal model predicts

$$\frac{dN}{dy} \propto \exp\left(\frac{-m}{T_{chem}}\right)$$

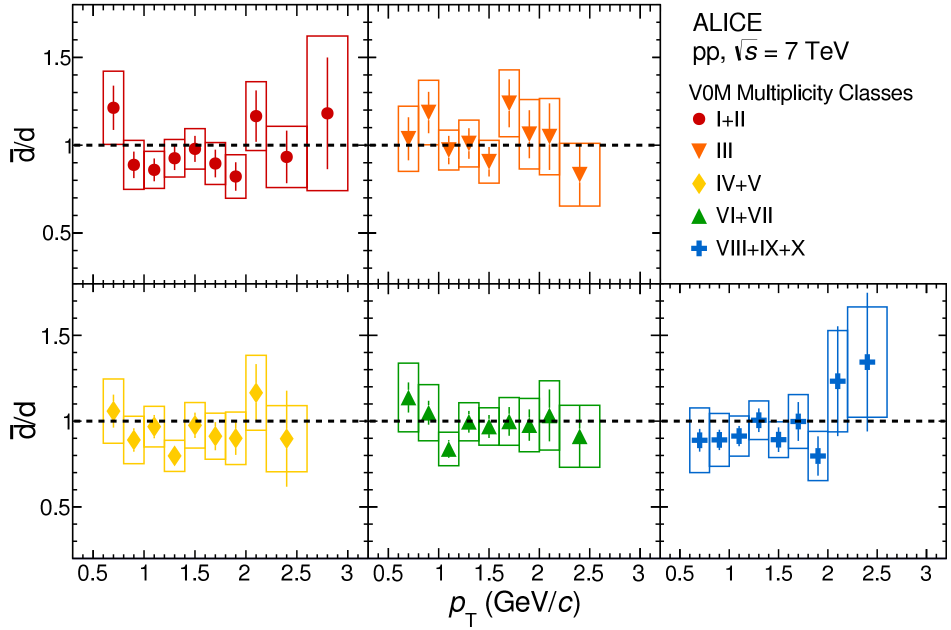
✓ Nuclei yields follow an exponential decrease with mass A for all collision systems.

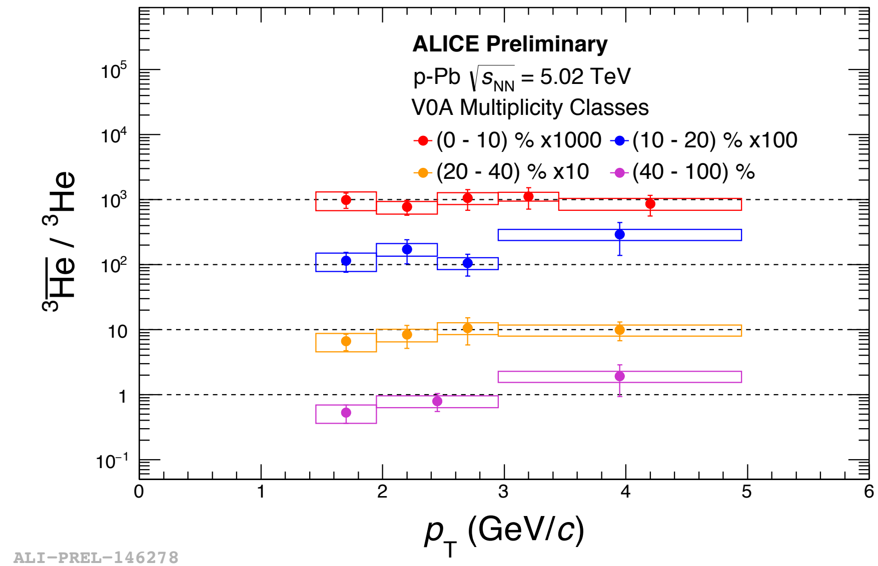
✓ Each added nucleon reduces yield by a factor called 'Penalty factor'

- Central Pb-Pb ~ 360
- NSD p-Pb ~ 640
- INEL pp ~ 950

Anti-matter to matter ratio

ALICE, PLB 794 (2019) 50-63





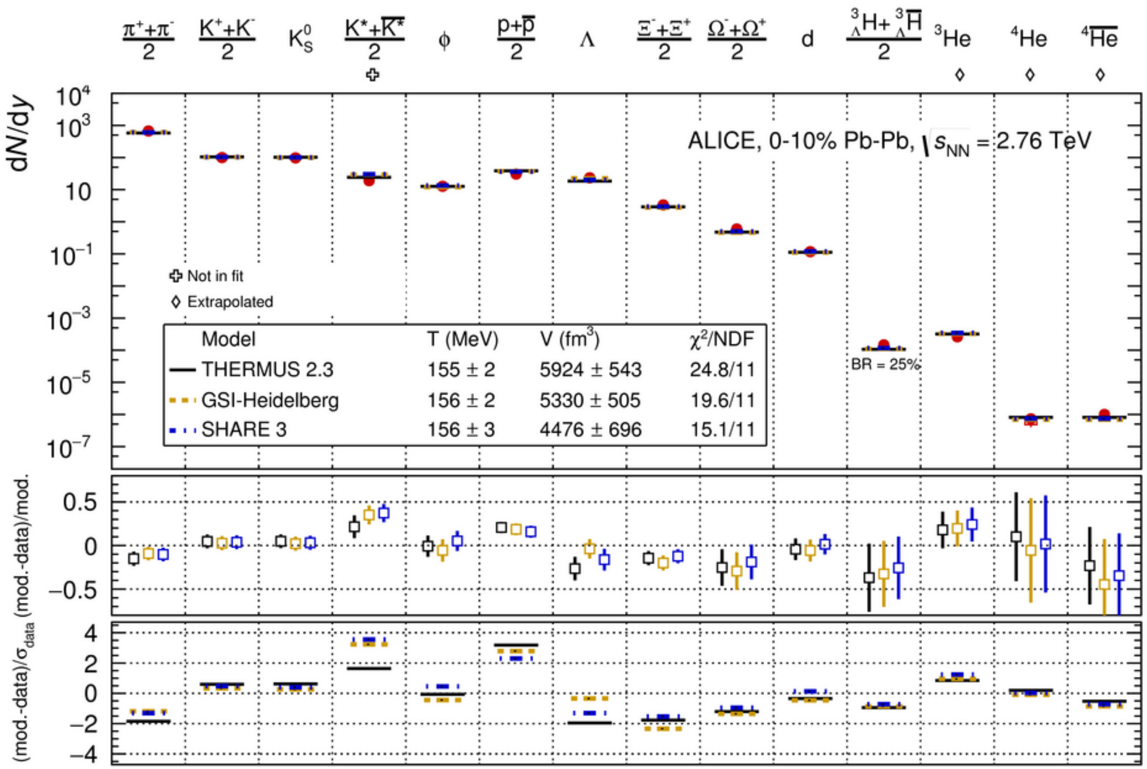
- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light particle species) → matter and anti-matter are produced in same abundance at LHC energies
- Ratios exhibit constant behavior as a function of p_T and centrality.
- Are in agreement with the coalescence and thermal model expectations.

Model Comparison: Thermal production, Kinetic freeze-out, and Coalescence

Thermal models fit to yields (Pb-Pb @ 2.76 TeV)

ALICE

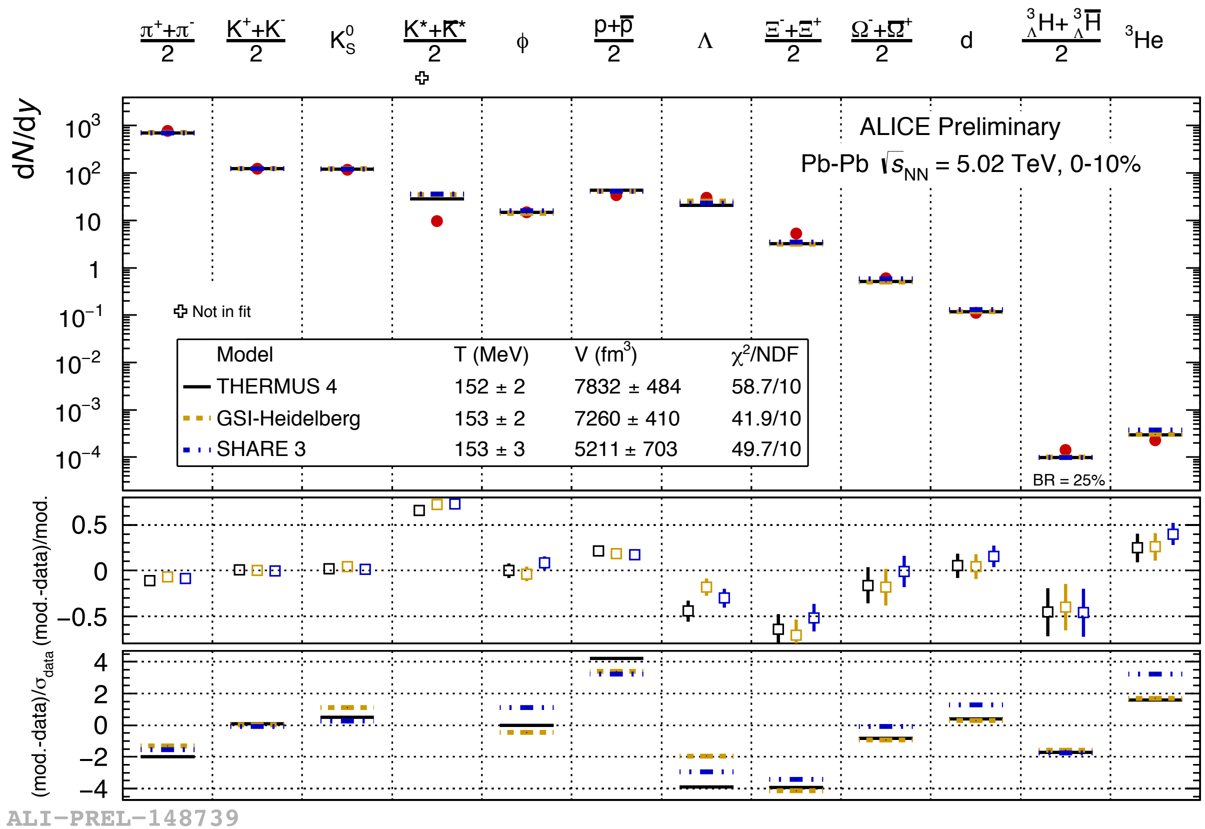
ALICE, NPA 971 (2018) 1-20



- Different models describe particle yields including light (hyper-)nuclei well with T_{chem} of about 156 MeV in Pb-Pb collisions at 2.76 TeV.
- Including nuclei in the fit causes no significant change in T_{chem}
  → hint for nuclei production at hadronization (binding energy of light nuclei ~ few MeV)
- This is in contrast to p-Pb and pp collisions.

THERMUS: Wheaton et al., Comp. Phys. Commun, 180 (2009) 84
GSI-Heidelberg: Andronic et al., Phys. Lett. B 673 (2009) 142
SHARE 3: Petran et al., Comp. Phys. Commun, 185 (2014) 2056

Thermal models fit to yields (Pb-Pb @ 5.02 TeV)



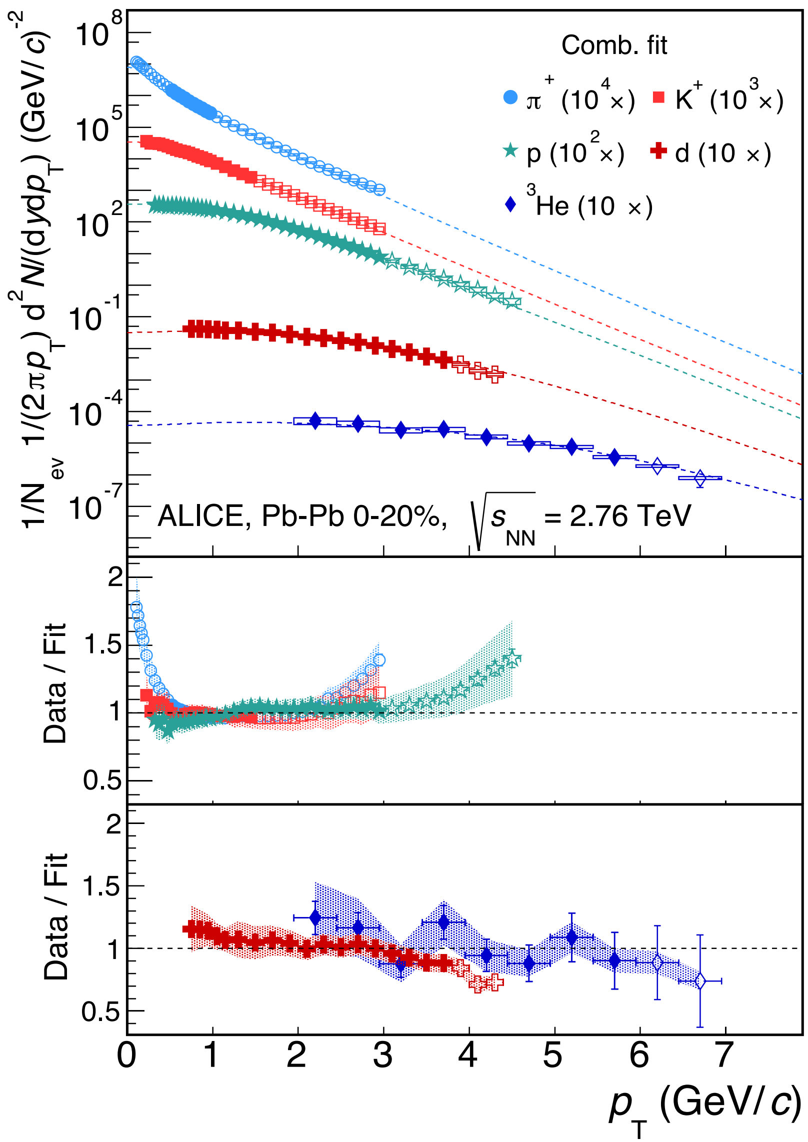
- Different models describe particle yields including light (hyper-)nuclei well with T_{chem} ~ 153 MeV in Pb-Pb collisions at 5.02 TeV.
- T_{chem} is slightly lower at 5.02 TeV than at 2.76 TeV.
- χ^2 is worse than at 2.76 TeV (mainly due to pions and protons).

THERMUS: Wheaton et al., Comp. Phys. Commun, 180 (2009) 84

GSI-Heidelberg: Andronic et al., Phys. Lett. B 673 (2009) 142

SHARE 3: Petran et al., Comp. Phys. Commun, 185 (2014) 2056

Combined Blast-Wave fit



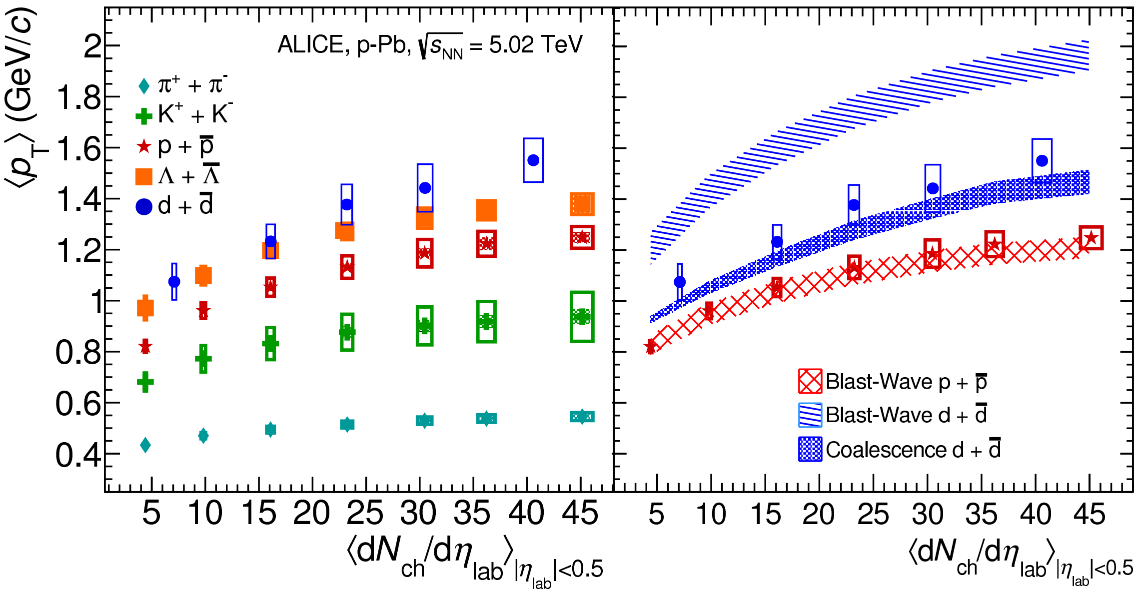
ALICE, PRC 93 (2015) 024917

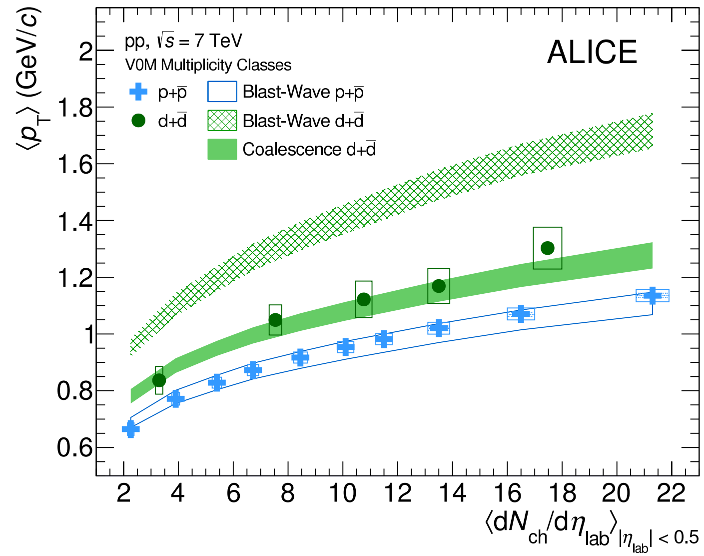
- ✓ π, K, p, d, and ^{3}He are fitted simultaneously for central Pb-Pb collisions with the Blast-Wave model in the limited p_T range.
- ✓ All particle spectra are described well with the BW fit.
- ✓ Common fit parameters are:
  $\langle\beta\rangle = 0.63 \pm 0.01$,
  $T_{kin} = 113 \pm 12$ MeV, and
  $n = 0.72 \pm 0.03$.
- ✓ Fit parameters are comparable to those from the combined BW fit to only π, K, and p.

<p_T> vs multiplicity

ALICE Coll.: [arXiv:1906.03136](https://arxiv.org/abs/1906.03136) [nucl-ex]

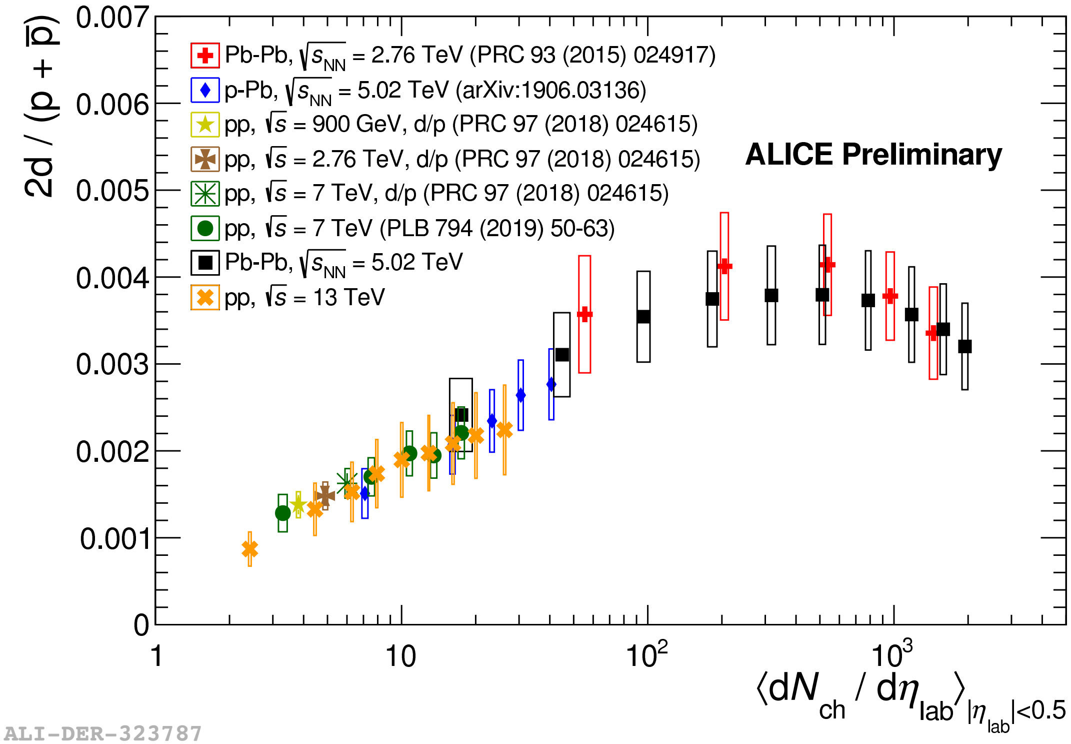
ALICE, PLB 794 (2019) 50-63





- ✓ <p_T> is consistent with the coalescence model expectations in both p-Pb and pp collisions for all multiplicity classes.
- ✓ Blast wave model fails to describe <p_T> for deuterons using common kinetic freeze-out parameters used for pi, K, and p in both pp and p-Pb collisions -- In contrast with the observation in Pb-Pb collisions.

Deuteron to proton ratio

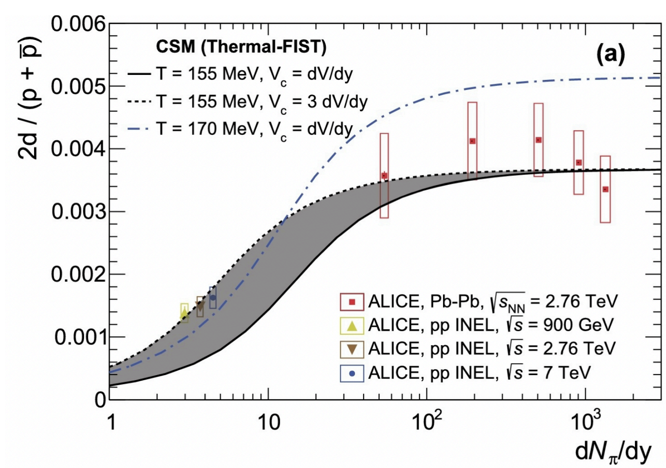


ALI-DER-323787

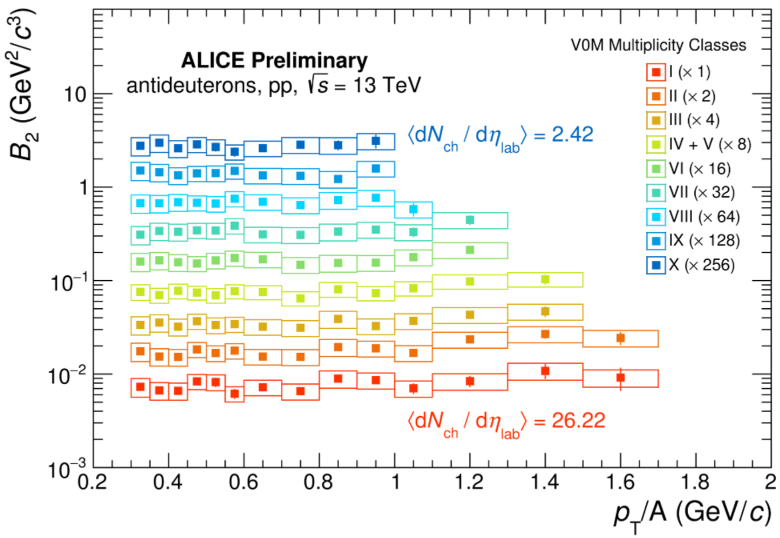
- Flat d/p ratio as a function of multiplicity implies ***thermal production***
  -- observed in Pb-Pb
- Increasing d/p ratio suggests ***coalescence production***
  -- observed in small systems
- *How to consistently describe ratio using single approach?*

Exact conservation of **baryon number**, charge, strangeness – qualitative description

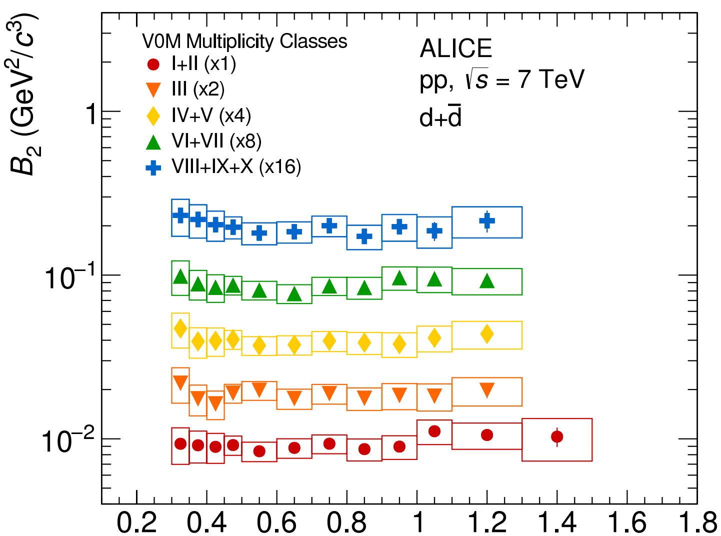
V. Vovchenko et al. Phys. Lett. **B785**, 171 (2018)



Coalescence parameter (B_2)



ALI-PREL-146141



ALICE, PLB 794 (2019) 50-63

- Coalescence parameter B_A relates the formation of composite nuclei to the one of primary protons and neutrons through a simple power law

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A$$

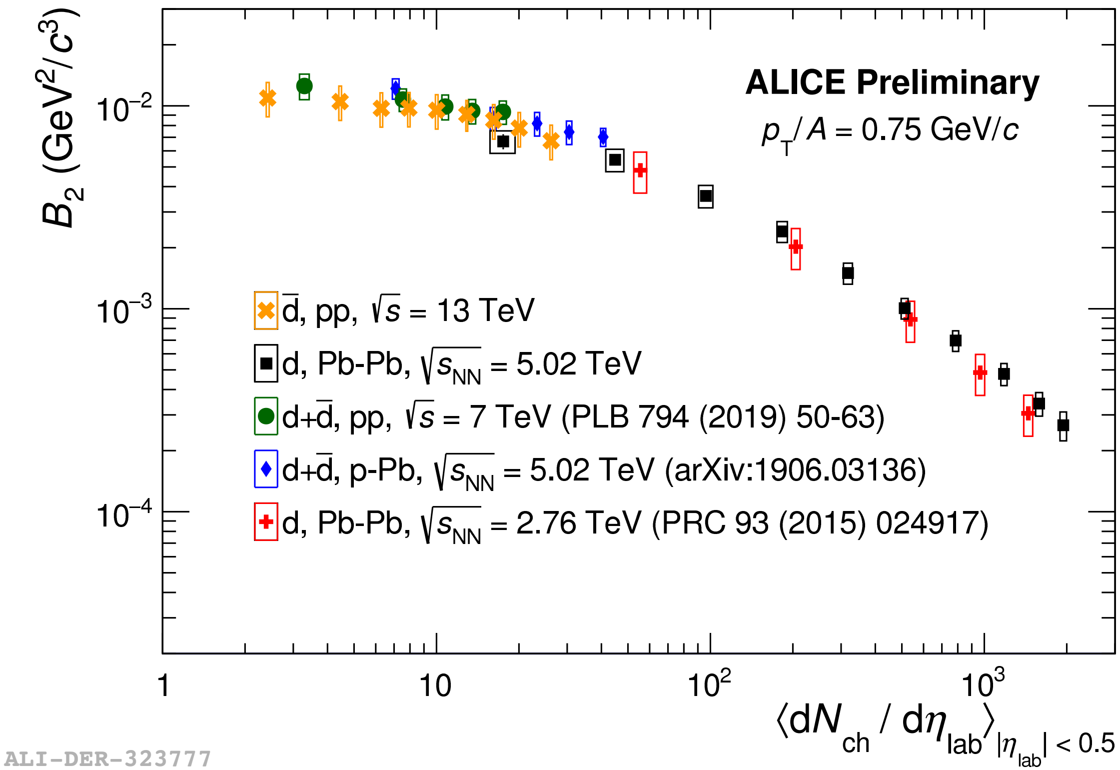
where $p_p = p_A/A$

- For A=2:

deuteron $\propto$ B_2 *x (proton)*^{2}

- B_2 does not show p_T dependence, in agreement with simple coalescence model.

Multiplicity dependence of B_2



- Coalescence probability decreases from pp to central Pb-Pb
- Smooth evolution with multiplicity
- Qualitative behavior explained by parameterization of coalescence parameter using the HBT radii:

$$\frac{B_2}{\mathrm{GeV}^2} \approx 0.068 \left[\left(\frac{R(p_T)}{1\mathrm{fm}} \right)^2 + 2.6 \left(\frac{b_2}{3.2\mathrm{fm}} \right)^2 \right]^{-3/2}$$

K. Blum et al., Phys. Rev. D 96 (2017) 103021

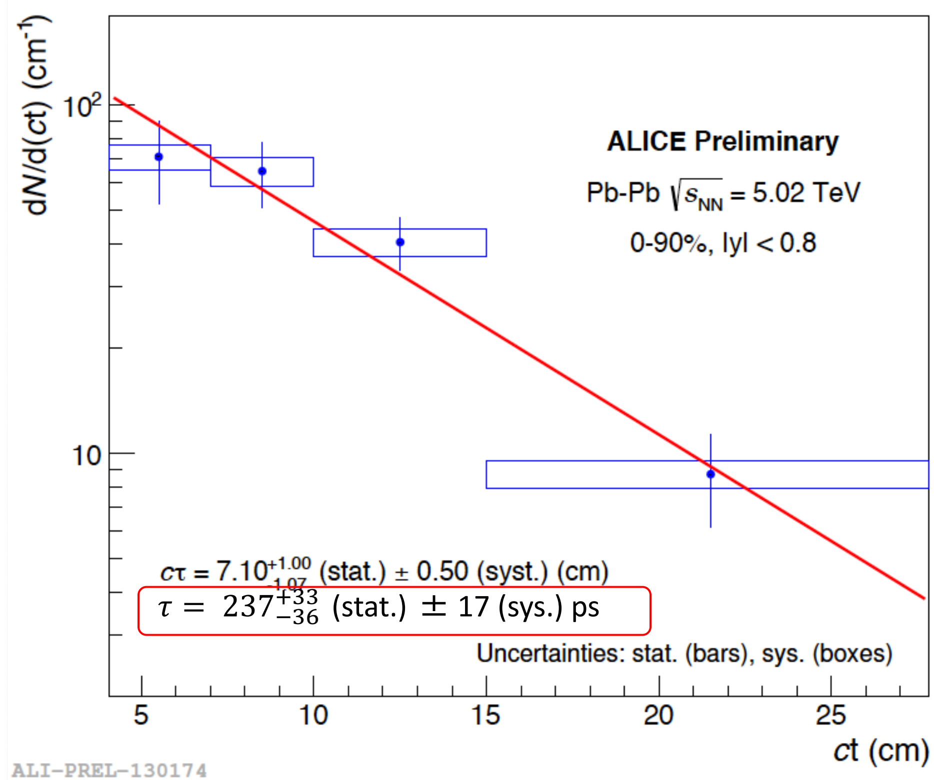
Hypertriton Lifetime

Hypertriton Lifetime

Hypertriton ($^{3}_{\Lambda}H$):
Bound state of p, n, and Λ
-- lightest hypernucleus

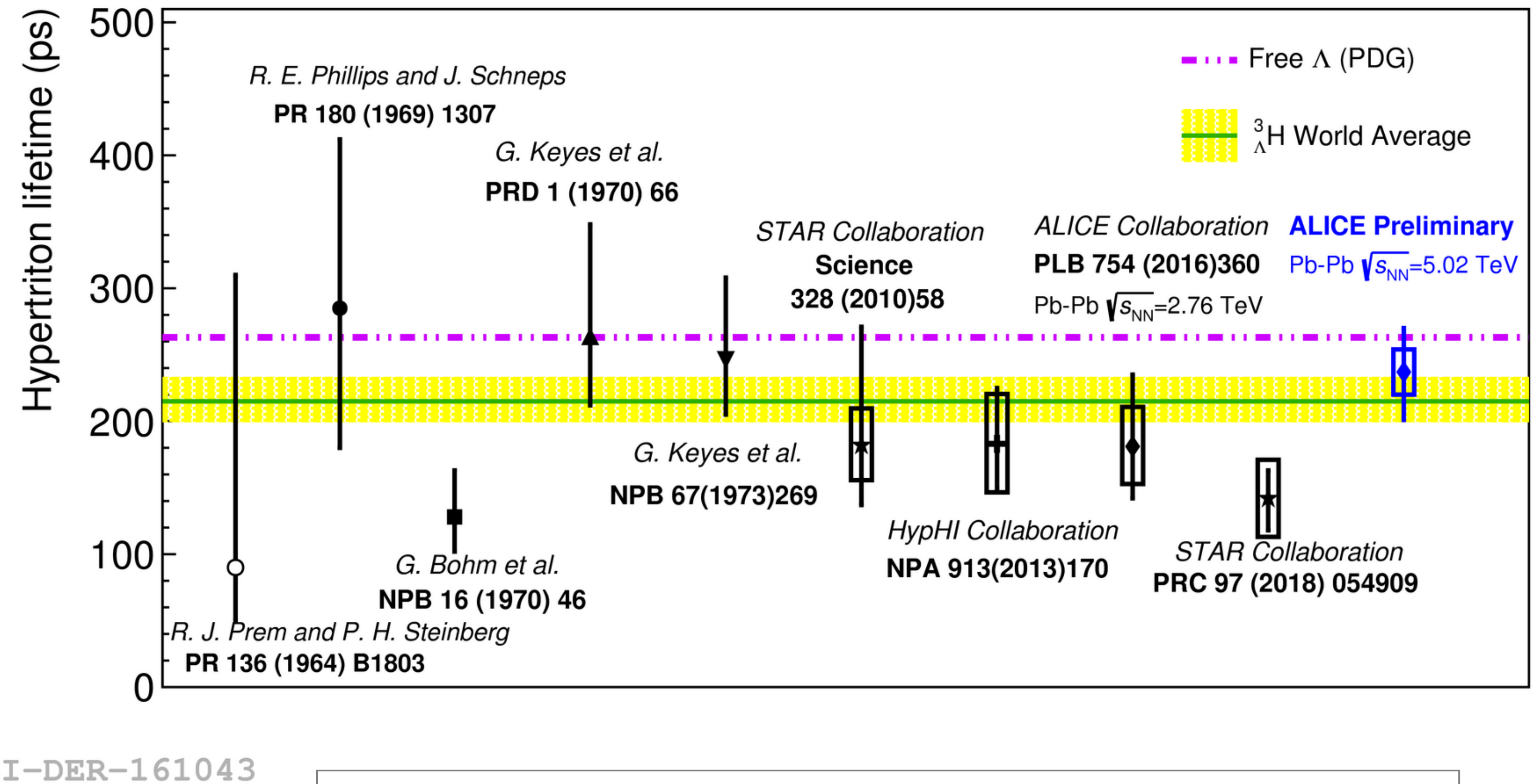
Small Λ separation energy led to hypothesis that $^{3}_{\Lambda}H$ lifetime is smaller than free Λ i.e. 263±2 ps

Property	Value
Mass	2.99116 ± 0.00005 (GeV/c²)
Λ binding energy	0.13±0.05 MeV
Lifetime (world average)	216^{+16}_{-19} ps
Decay modes studied	$^{3}He\ \pi^-$ (37.3%) $d\ p\ \pi^-$ (60.1%)



Full statistics data of Pb-Pb collisions at 5.02 TeV analyzed

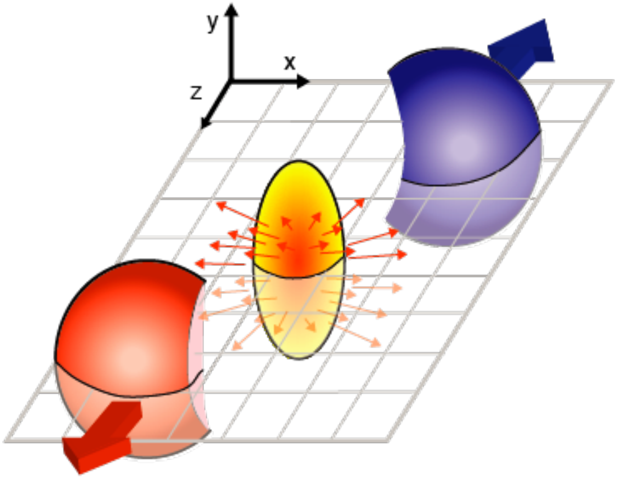
Comparison with World Data



- Improved precision lifetime measurement
- Compatible with world average and free Λ lifetime

Flow Measurements

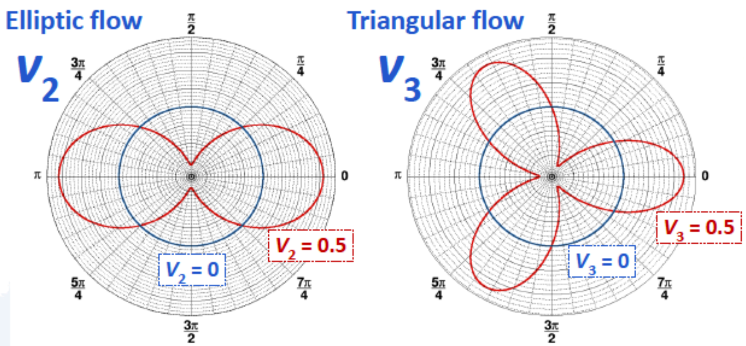
Anisotropic Flow



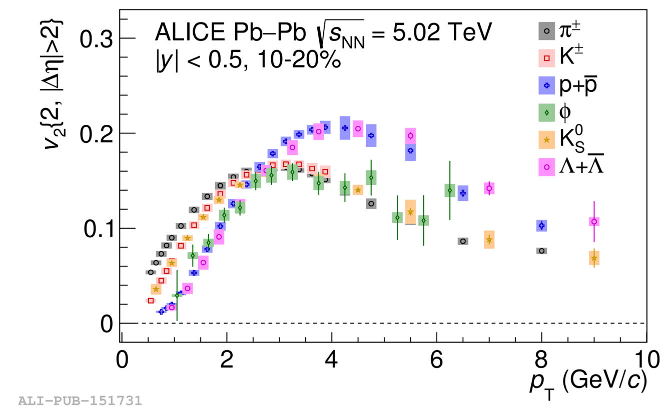
Strongly interacting system:
Spatial anisotropy → momentum anisotropy
Quantified in terms of Fourier coefficients v_n

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[(\varphi - \Psi_n)]\right)$$

$$v_n(p_T, y) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

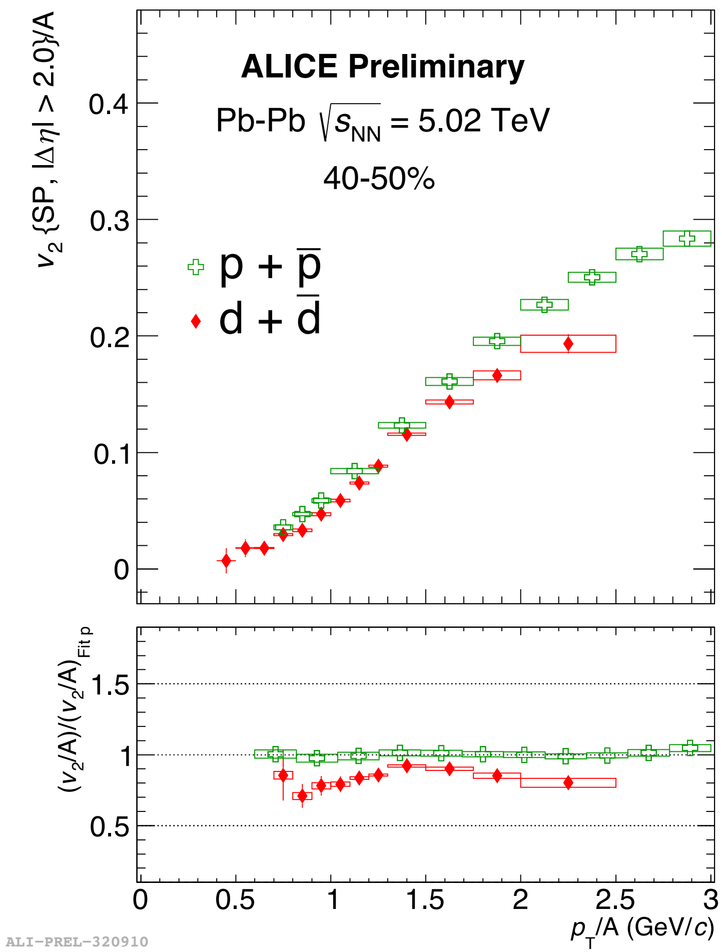


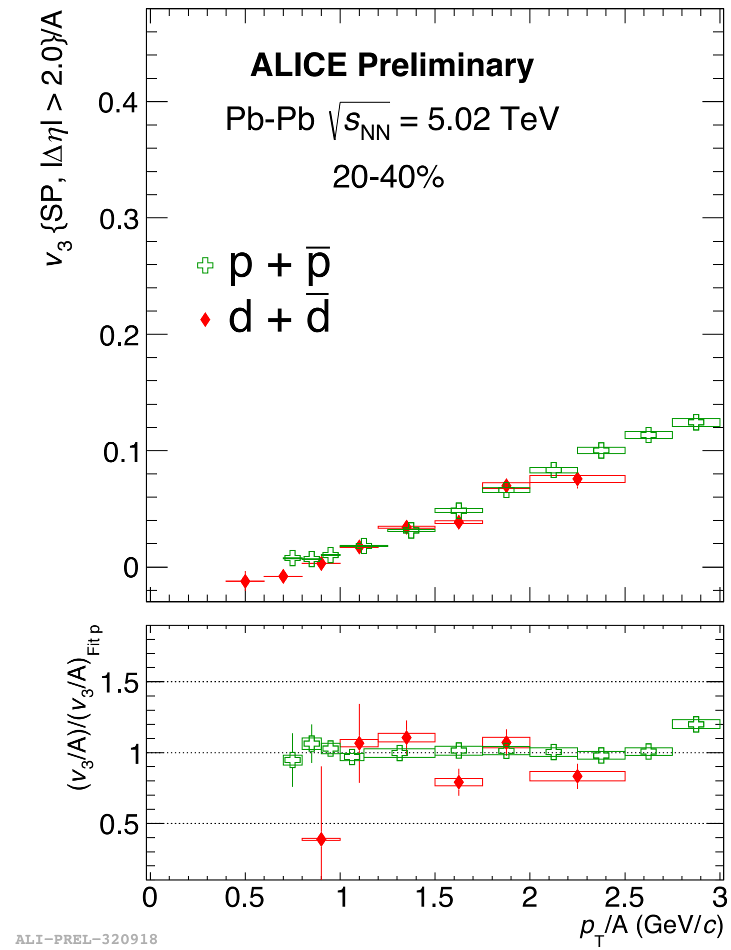
ALICE, JHEP 09 (2018) 006



Observed flow for light flavor particles is consistent with quark coalescence.
-- Does nucleon coalescence hold for (anti-)nuclei?

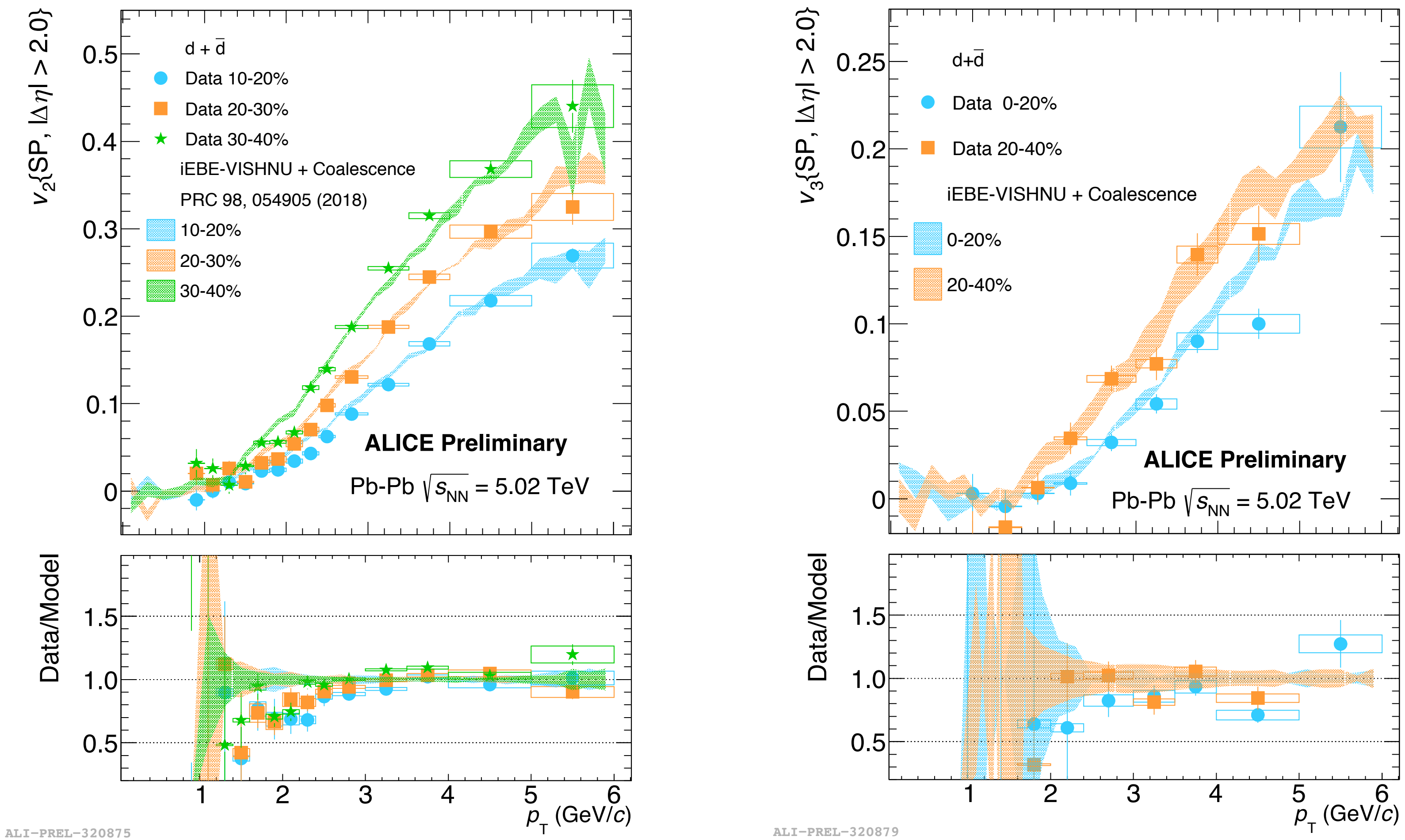
Deuterons v_2 and v_3 in Pb-Pb collisions





(Anti-)deuteron v_2 and v_3 comparable to protons.

Deuterons v_2 and v_3 in Pb-Pb collisions



(Anti-)deuteron v_2 and v_3 is in agreement with the coalescence model using protons and neutrons phase-space distribution from iEBE-VISHNU.

(Anti-) Deuteron Cross-section Measurement

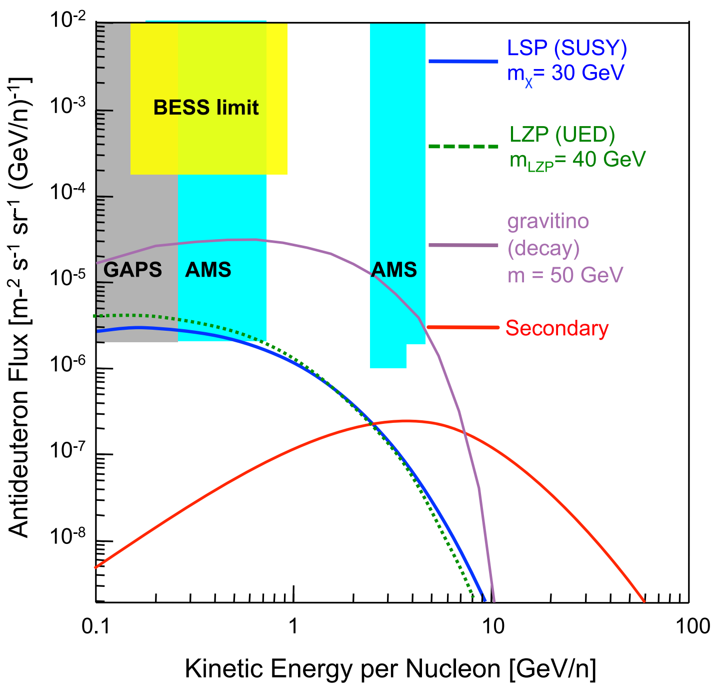
Anti-Deuteron Searches in Dark Matter

- Most used probes for the indirect search for dark matter annihilation or decay are e^+, $\bar{p}$, γ-rays etc.
  -- But they suffer from high and uncertain background from cosmic ray spallation etc.

- Cosmic ray anti-deuterons have been proposed as good probe for dark matter searches.

- The pp collision results of anti-deuteron production are important in estimating the secondary anti-deuteron flux in cosmic rays.

- For better results: Need to understand the production and absorption cross-section from experiments.

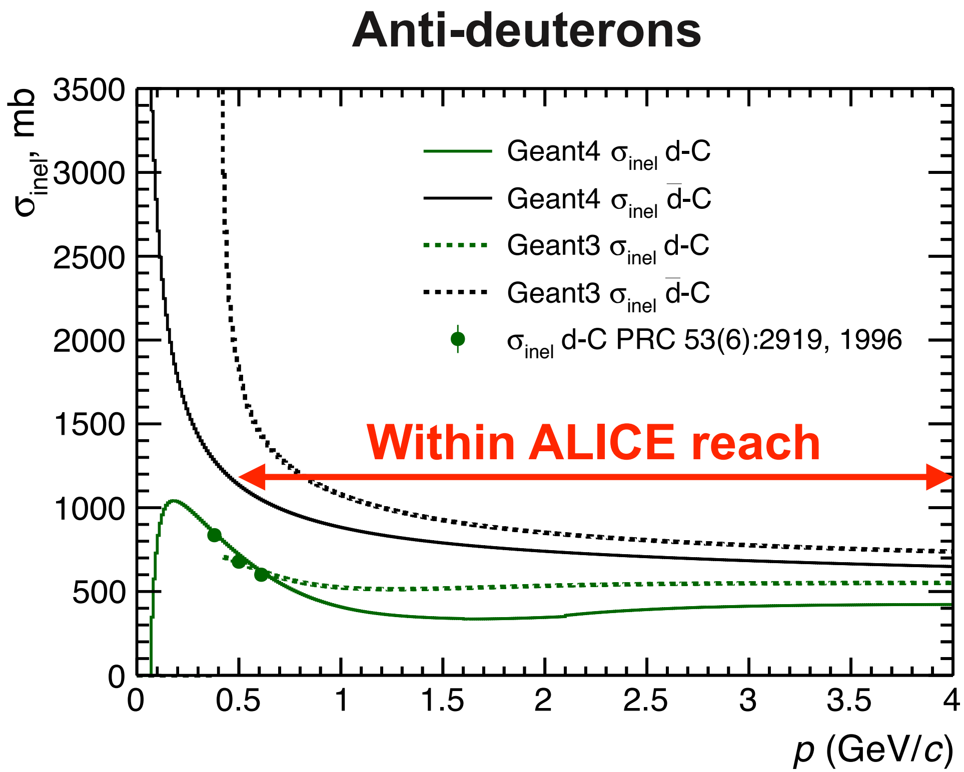


T. Aramaki et al., Physics Reports 618 (2016) 1–37

Role of ALICE Experiment

Anti-deuterons are measured in ALICE in pp collisions at various $\sqrt{s}$ = 0.9 – 13 TeV.

Attempts have been made to constrain the inelastic cross-section of anti-deuterons with ALICE data
-- By studying anti-deuteron absorption in detector material.



Low momentum absorption cross-section of (anti-)deuteron is not available in any experiment (No experimental data below p_{lab} = 13.3 GeV/c)

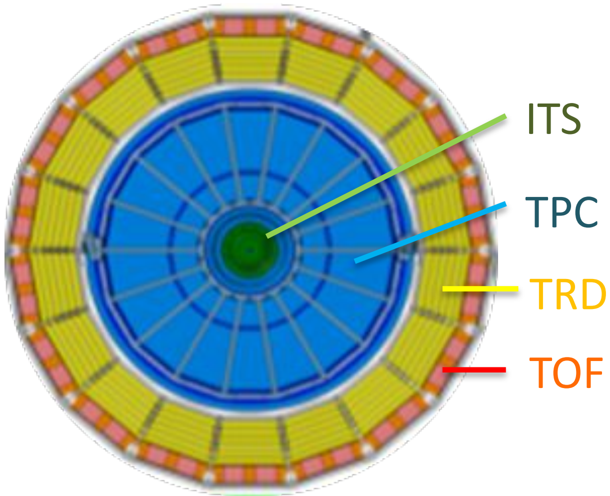
ALICE can be used to study absorption in detector material at *low momentum*

ALICE Apporach

Material Budget:

ALICE detector material budget at mid-rapidity:

- Beam pipe (~0.3% X_0): beryllium
- ITS (~8% X_0): silicon detectors, carbon supporting structures
- TPC (~4% X_0): Ar/CO_2 gas (88/12)
- TRD (~25% X_0): carbon/polypropylene fibre radiator, Xe/CO_2 gas, carbon supporting structures
- Space frame (~20% X_0 between TPC and TOF detectors): stainless steel

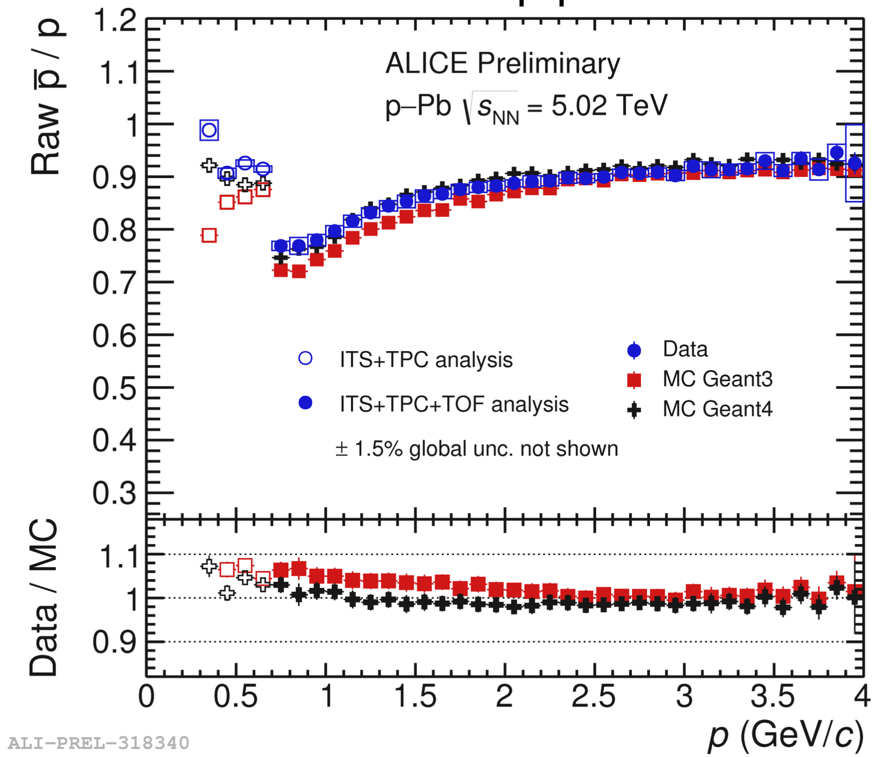


Approach:

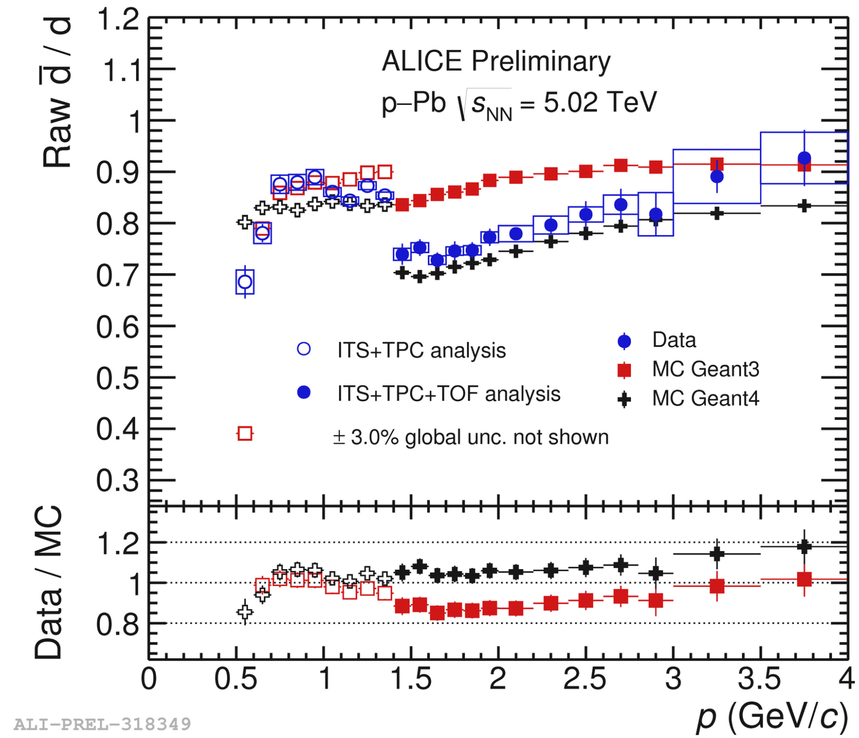
- At LHC energies particles and anti-particles are produced in equal abundance.
- Measure raw anti-particle/particle ratios
- Correct for (anti-)particles produced in weak decays and knock-out from detectors material
- Ratio not equal to unity ➔ loss of anti-particles in detector material due to annihilation
- Constrain $\sigma_{inel}(\bar{d})$ via comparison with Monte Carlo simulations based on Geant

Raw anti-particle/particle ratio in ALICE

Raw: anti-p/p



Raw: anti-d/d



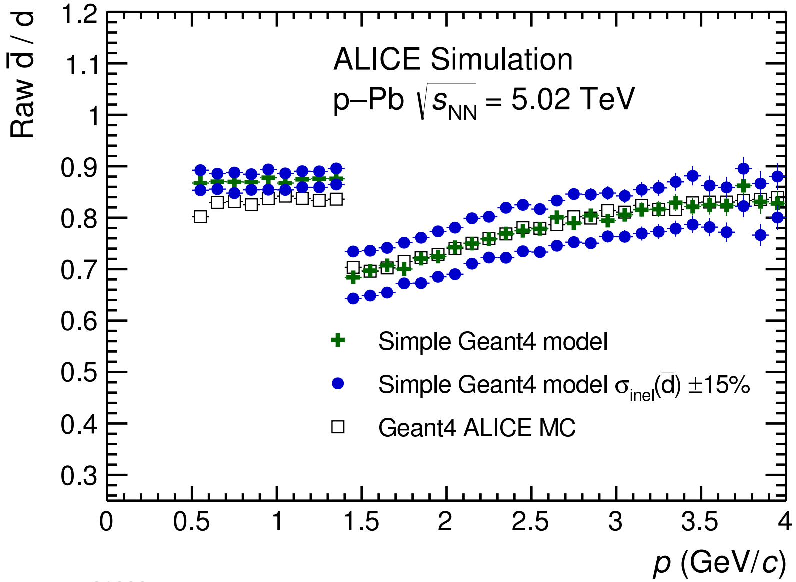
Geant4 based Monte Carlo simulations are in better agreement with the experimental data.

Note: Step at *p*=0.7 GeV/c in $\bar{p}$/p and at *p*=1.4 GeV/c in $\bar{d}$/d ratios are due to additional detector material between TPC and TOF (TRD and space frame).

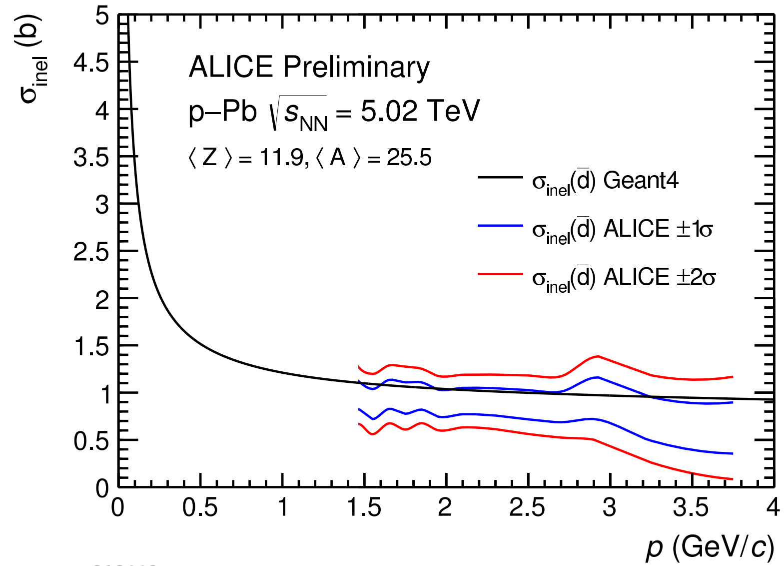
Preliminary Constraint on Anti-Deuteron σ_{INEL}

Standalone Geant4 simulation to understand ratios in more details

- (Anti-)deuteron source + a target made of ALICE detector materials
- Loss of (anti-)particles due to inelastic processes in detector material
    - low p: beam pipe, ITS, TPC (<Z> = 7.4, <A> = 14.8)
    - high p: beam pipe, ITS, TPC, TRD, SF (<Z> = 11.9, <A> = 25.5)



ALI-SIMUL-318390



ALI-PREL-318449

- σ_{inel} has been estimated for an ‘average element’ of detector material from primary collisions to TOF detector <Z> = 11.9, <A> = 25.5.
- Improving statistical and systematic uncertainties on data for tighter constraints.
- Extending anti-deuterons analysis toward low momentum.

Summary and conclusions

ALICE

- ✓ Nuclei production (up to A=4) has been measured by the ALICE experiment.
- ✓ Obtained deuteron and ^{3}He spectra in pp, p-Pb and Pb-Pb collisions. Hardening of deuteron spectra with multiplicity is observed for all the systems.
- ✓ π, K, p, d, and ^{3}He spectra in central Pb-Pb collisions are well described by a single set of common freeze-out parameters in the Blast-wave model.
- ✓ The nuclei yields follow an exponential decrease with mass for all three systems. The penalty factor is ~360 in Pb-Pb collisions, ~640 in p-Pb collisions and ~950 in pp collisions. The decrease in Pb-Pb reflects thermal behavior described by T_{chem}.
- ✓ Both coalescence and thermal models describe different aspects of the data.
  - ➢ Thermal model describes particles and light nuclei yields (including hypertritons) well at $T_{chem} \approx 156$ MeV in Pb-Pb collisions.
  - ➢ d/p ratio rises with multiplicity in pp and p-Pb but remains constant for Pb-Pb.
  - ➢ $\langle p_T \rangle$ is consistent with the coalescence model expectations in pp and p-Pb collisions

Summary and conclusions

- ✓ Coalescence parameter (B_2): Coalescence probability decreases from pp to central Pb-Pb collisions. Smooth evolution with event multiplicity is observed.
- ✓ Hypertriton lifetime: Lifetime is compatible with the world's average and free Λ lifetime.
- ✓ Flow: Anti-deuteron v_2 and v_3 are in agreement with the coalescence iEBE-VISHNU model for all centrality classes.
- ✓ Annihilation cross-section: Anti-deuterons σ_{inel} has been estimated for an 'average element' of detector material ($\langle Z \rangle = 11.9$, $\langle A \rangle = 25.5$) at momentum 1.4 GeV/c to 4 GeV/c.

Outlook: ALICE Upgrade

ALICE Upgrade

ALICE has started a huge upgrade in preparation for LHC Run3 and Run4

→ expected Pb-Pb $\int\mathcal{L}$ = 10 nb^{-1} at 50 kHz collision rate

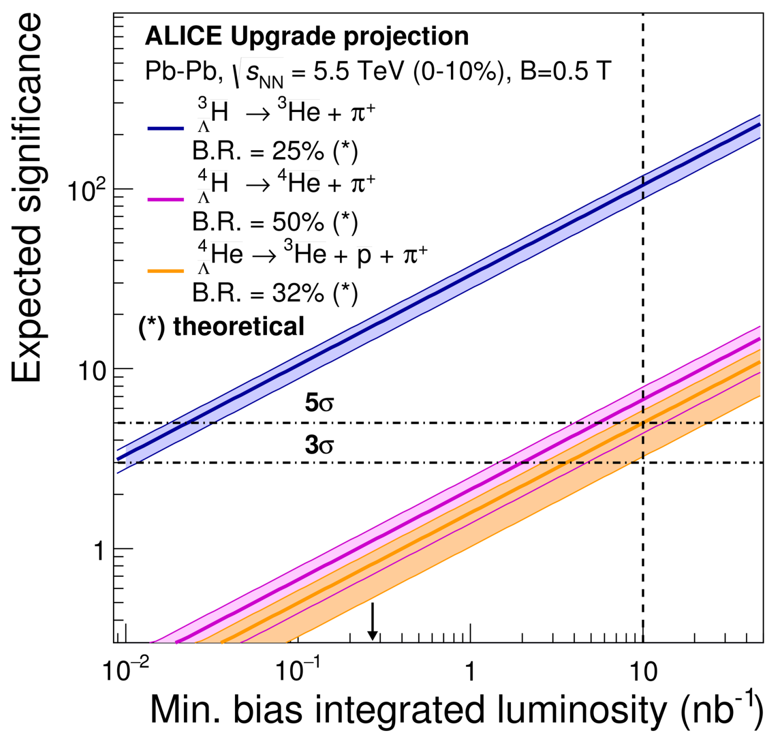
Quantity	design	achieved				upgrade
Year	(2004)	2010	2011	2015	2018	≥2021
Weeks in physics	-	4	3.5	2.5	3.5	-
Fill no. (best)		1541	2351	4720	7473	-
Beam energy $E[Z\ \mathrm{TeV}]$	7	3.5		6.37	6.37	7
Pb beam energy $E[A\ \mathrm{TeV}]$	2.76	1.38		2.51	2.51	2.76
Collision energy $\sqrt{s_{NN}}$ [TeV]	5.52	2.51		**5.02**	**5.02**	5.52
Bunch intensity N_b [10^8]	0.7	1.22	1.07	2.0	2.2	1.8
No. of bunches k_b	592	137	338	518	733	1232
Pb norm. emittance ϵ_N [μm]	1.5	2.	2.0	2.1	2.0	1.65
Pb bunch length σ_z m	0.08	0.07–0.1				0.08
β^* [m]	0.5	3.5	1.0	0.8	0.5	0.5
Pb stored energy MJ/beam	3.8	0.65	1.9	8.6	13.3	21
Luminosity L_{AA} [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	0.03	0.5	3.6	6.1	7
NN luminosity L_{NN} [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	43	1.3	22.	156	264	303
Integrated luminosity/experiment [$\mu\mathrm{b}^{-1}$]	1000	9	160	433,585	900,1800	10^4
Int. NN lumi./expt. [pb^{-1}]	43	0.38	6.7	19,25.3	39,80	4.3×10^5

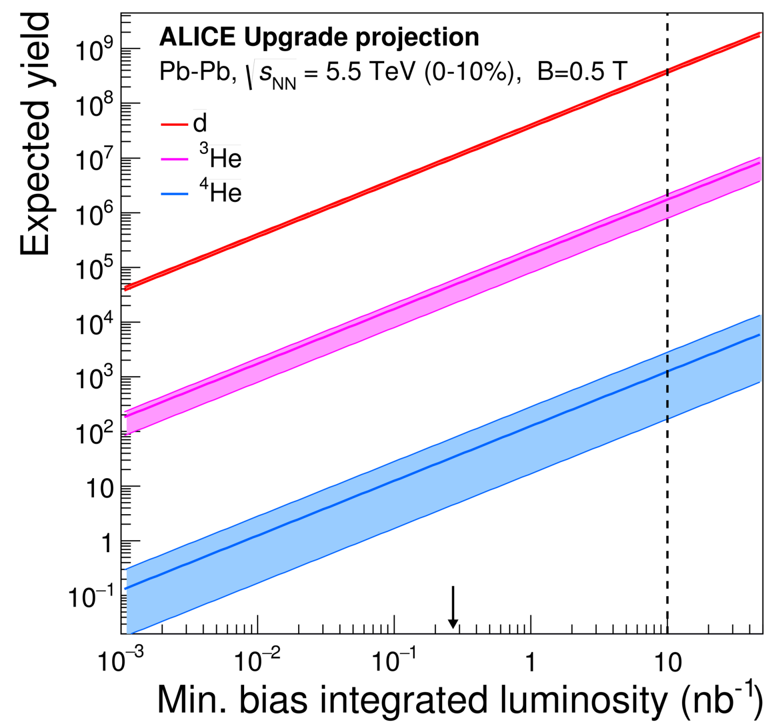
Citron et al., arXiv:1812.06772 [hep-ph] 25 Feb 2019

ALICE Upgrade

ALICE has started a huge upgrade in preparation for LHC Run3 and Run4
→ expected Pb-Pb $\int\mathcal{L}$ = 10 nb^{-1} at 50 kHz collision rate

Possibility to investigate A=4 (anti-)hypernuclei and A=5 (anti)nuclei and improve accuracy for A=3 (hyper)nuclei





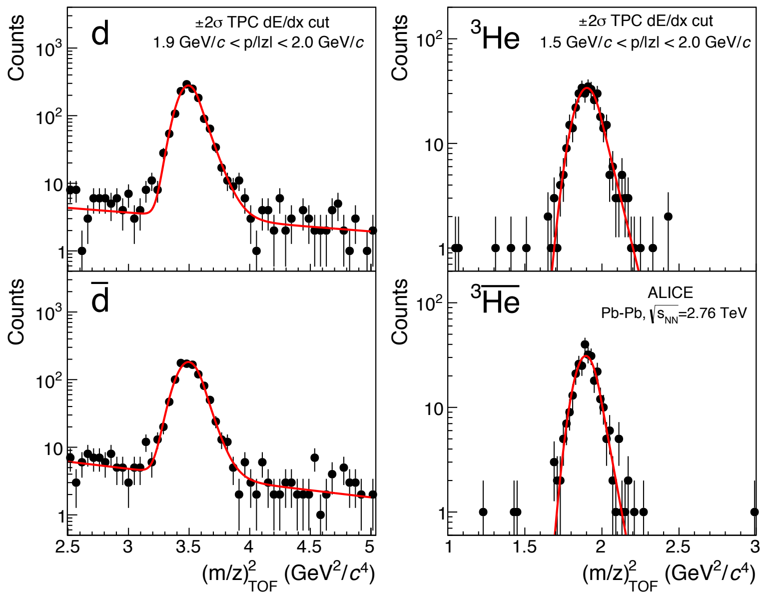
Citron et al., arXiv:1812.06772 [hep-ph] 25 Feb 2019

Thank you

Back up

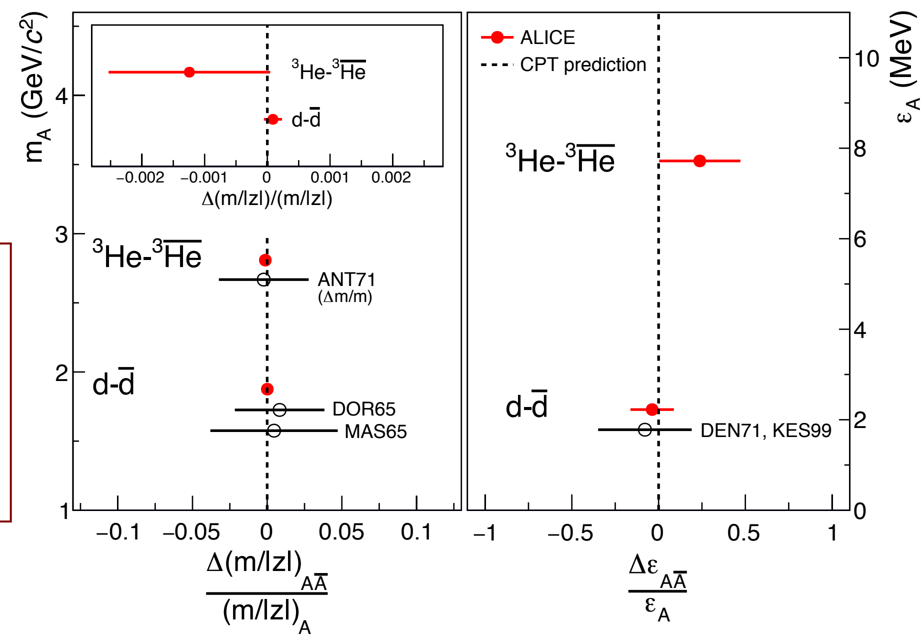
Mass difference nuclei/anti-nuclei

ALICE Coll: **Nature Phys. doi:10.1038/nphys3432**



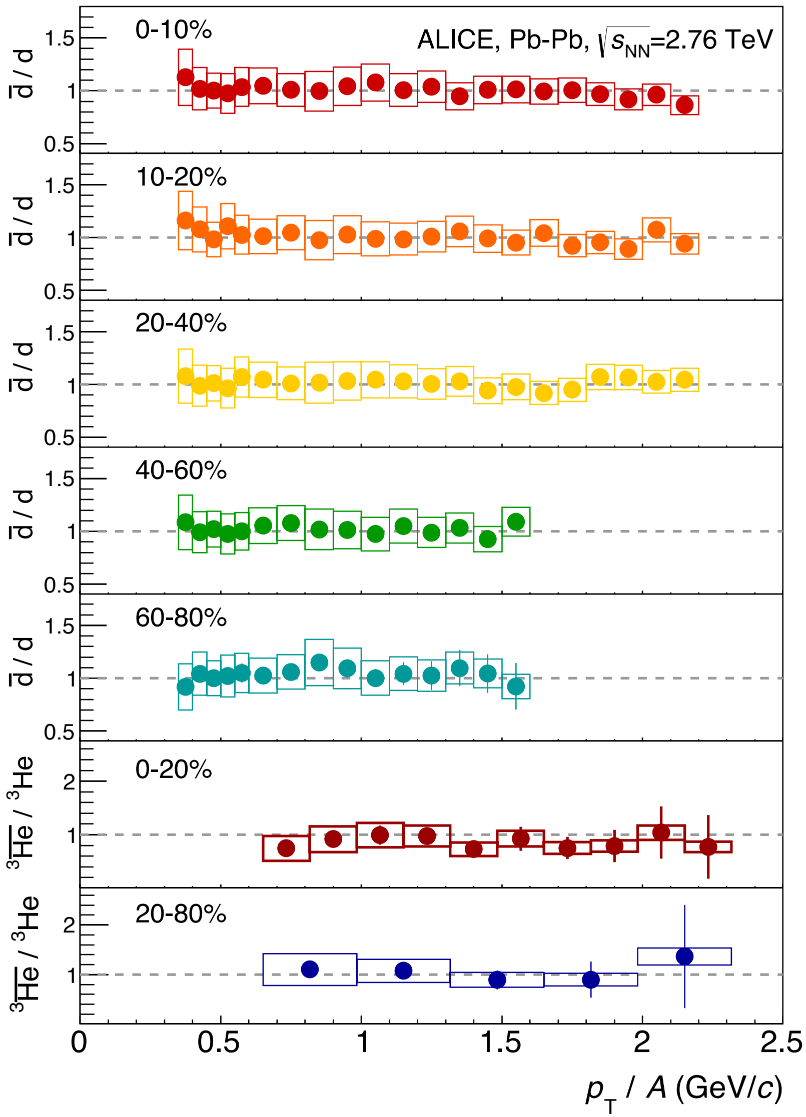
The precise measurement of (anti-)nuclei mass difference allows probing any difference in the interaction between nucleons and anti-nucleons.

Performed test of the CPT invariance of residual QCD "nuclear force" by looking at the mass difference between nuclei and anti-nuclei.



- ✓ Mass and binding energies of nuclei and anti-nuclei are compatible within uncertainties.
- ✓ Measurement **confirms the CPT invariance** for light nuclei.

Anti-matter to matter ratio

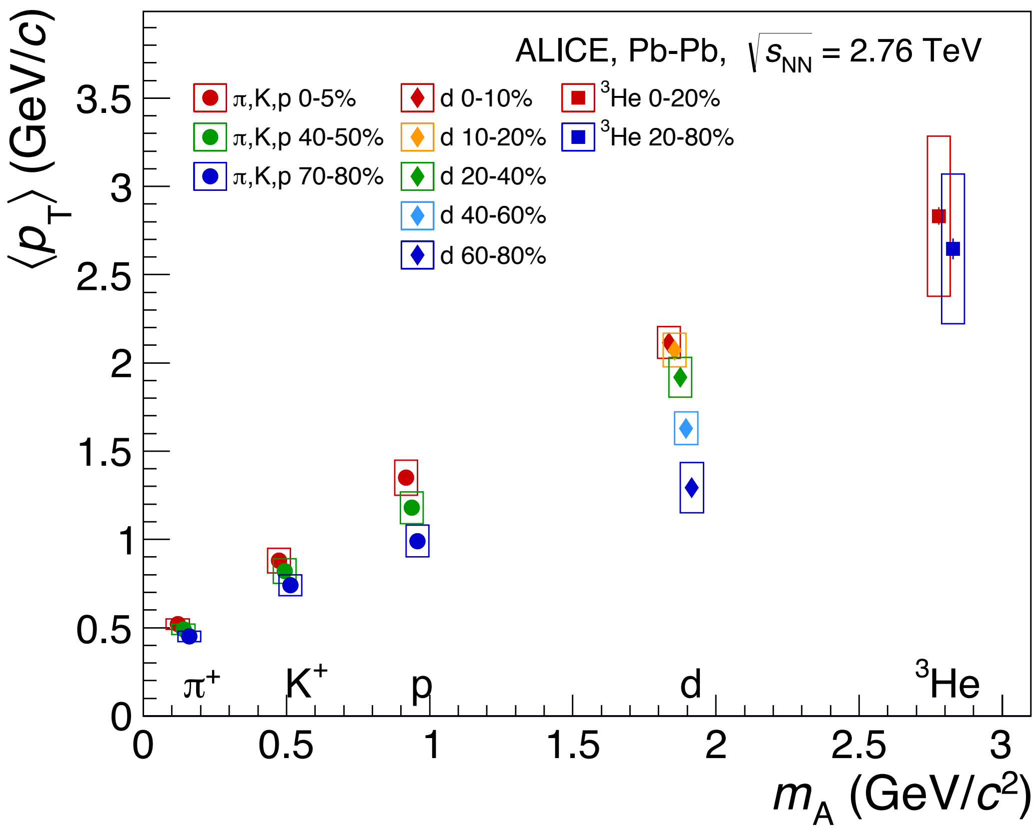


ALICE, PRC 93 (2015) 024917

- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light particle species).
- Ratios exhibit constant behavior as a function of p_T and centrality.
- Are in agreement with the coalescence and thermal model expectations.

$<p_T>$ vs mass (in Pb-Pb)

ALICE, PRC 93 (2015) 024917



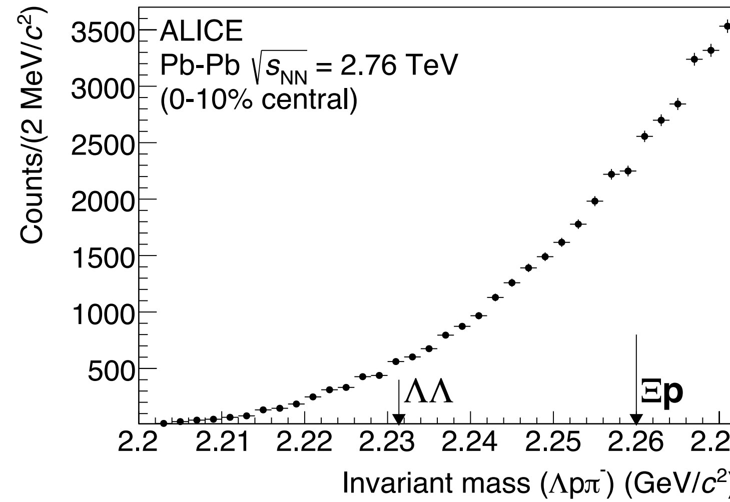
✓ $<p_T>$ increases with increasing particle mass.

Searches for exotica

Thermal models predict the abundances of nuclei correctly and therefore can be used as prediction for weakly decaying exotic bound states like ΛΛ and Λn-bar.

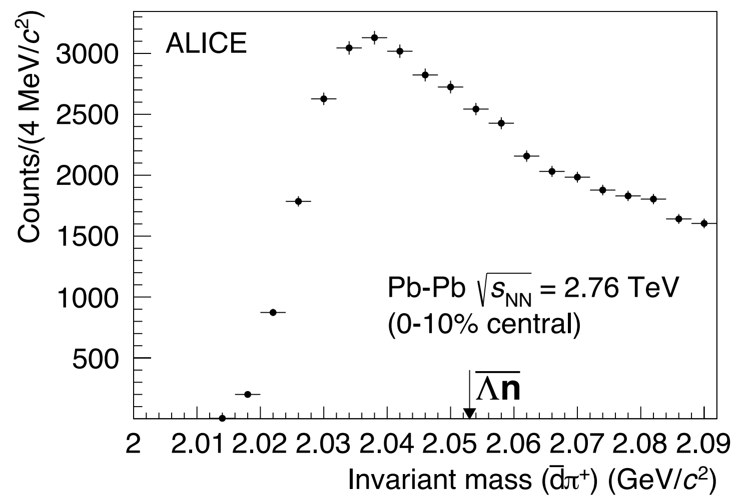
ΛΛ (H-dibaryon)

- Predicted by Jaffe in bag model calculations
  R. L. Jaffe, PRL 38, 195 (1977).
- Decay channel: $\Lambda\Lambda \rightarrow \Lambda + p + \pi^-$
- Thermal model prediction at T_{chem} = 156 MeV is dN/dy = 6.03×10^{-3}.



Λn-bar

- Decay channel: $\overline{\Lambda n} \rightarrow \bar{d} + \pi^+$
- Thermal model prediction at T_{chem} = 156 MeV is dN/dy = 4.06×10^{-2}.



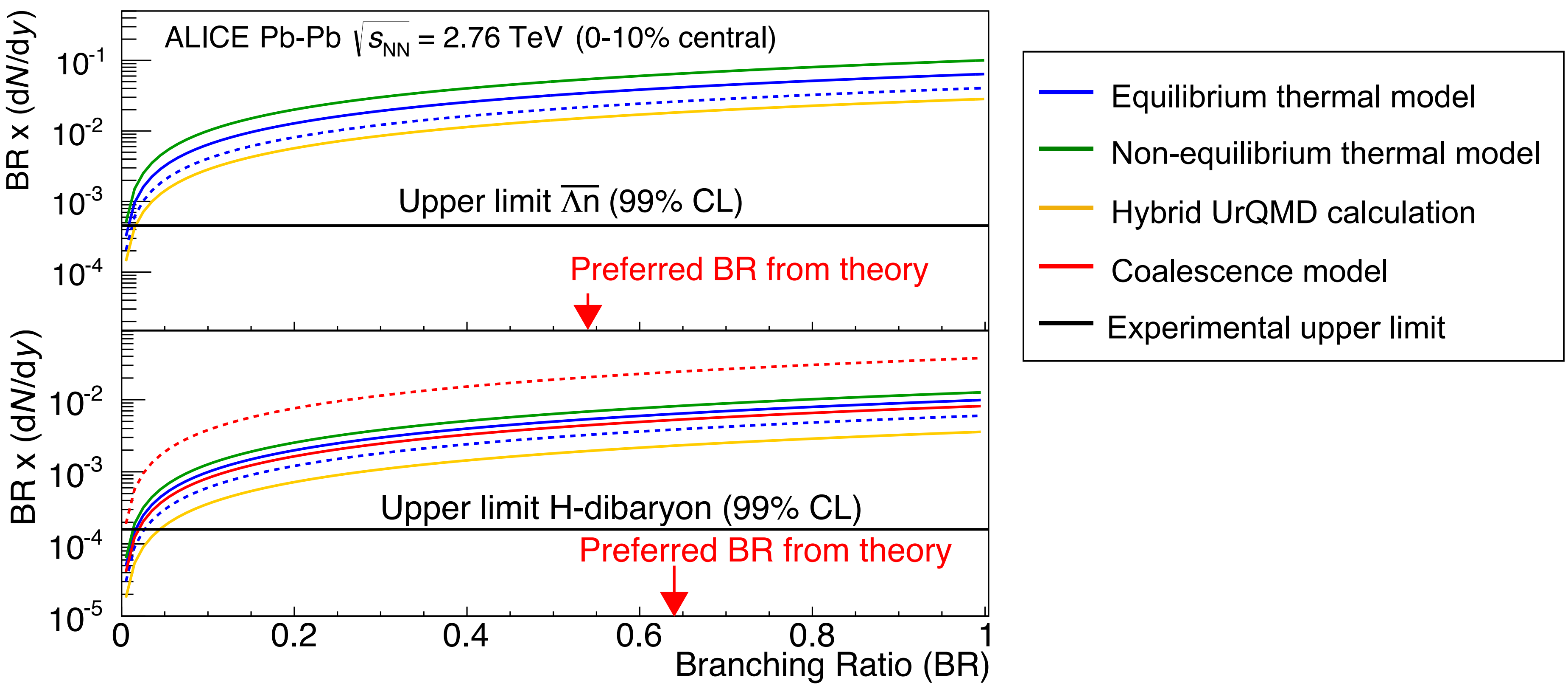
ALICE, PLB 752 (2016) 267-277

- ✓ Both ΛΛ and Λn-bar are expected to be seen with the statistics available in ALICE.
- ✓ No signal visible in the invariant mass spectra.
- ✓ From the non observation, upper limit set on d*N*/dy for ΛΛ and Λn-bar bound states.

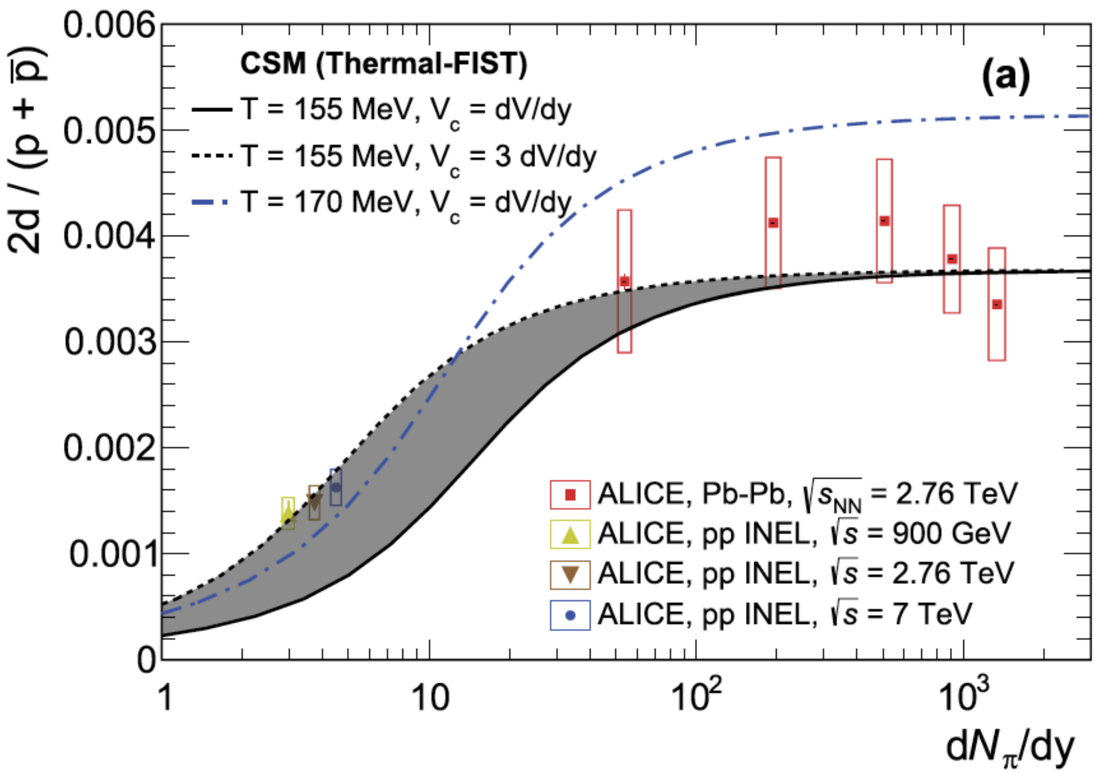
Exotic searches: Upper limit

ALICE, PLB 752 (2016) 267-277

Experimentally determined upper limit for ΛΛ and Λn-bar bound states compared with the models calculation as a function of BR.



(Anti-) Nuclei Production: Model Comparison



V. Vovchenko et al. Phys. Lett. **B785**, 171 (2018)

Canonical Statistical Model (CSM): Thermal-FIST package

- Exact conservation of **baryon number**, electric charge, strangeness

Explains the trend observed in experimental data of nuclei over proton ratio